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CALCULATING THE GROWTH OF PONDEROSA PINE FORESTS

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By

Philip A. Briegleb

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December 28, 1945

CALCULATING THE GROWTH OF PONDEROSA PINE FORESTS

A Progress Report

By

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FOREWORD

Early studies by the Pacific Northwest Forest Experiment Station resulted in the publication in 1934 of U.S.D.A. Technical Bulletin 407, "Growth in Selectively Cut Ponderosa Pine Forests of the Pacific Northwest" by Dr. Walter H. Meyer (8).[2/] That bulletin contains a wealth of perennially useful basic information, but since it was prepared before light selection cutting became prevalent and before the Keen tree classification was generally adopted, it does not contain all the data now needed and in the form needed by the practicing forester.

Since Dr. Meyer's bulletin was prepared further studies of ponderosa pine growth and mortality have been made by the present author and others at this Station and particularly by F. P. Keen of the Forest Insect Laboratory of the Bureau of Entomology and Plant Quarantine. The latter generously put a large amount of basic data at the disposal of the author for analysis which has been used freely and has greatly enriched the present paper.[3/]

This text employs the Keen tree classification (5) instead of the Dunning system (4) used in the earlier bulletin No. 407. It presents procedures of growth estimation designed for application to a wide range of selective cutting. Some of the tables used herein have already been published, mainly in Forest Research Notes No. 32 (2).

1/ Mr. Briegleb is now on the Staff of the Northeastern Forest Experiment Station, Philadelphia, Penn.

2/ Numbers in parentheses refer to literature cited, listed at the conclusion of this paper.

3/ In addition to Dr. Meyer and to Mr. Keen, the author is indebted particularly to Mr. Donald Bruce for helpful suggestions, to Mr. Wesley Zellner for much of the computing work, and to Dr. Thornton T. Munger under whose general direction much of this research was done and who has edited and otherwise contributed to the completion of this manuscript.

The present paper must be regarded as a progress report and not as a final treatise on this involved subject. More study needs to be made of stands which have been selectively cut for a term of years. Of necessity the growth and mortality data now available are based largely on records of virgin forests and those only relatively recently cut by the selection method. It is hoped that local studies will be continued by various agencies to furnish data, particularly on growth after selective cutting, that will apply accurately to specific conditions.

It is hoped that this progress report will prove valuable, first, as a summary of growth data now available, second, as a manual of procedures for applying these data to aid in the solution of everyday pine management problems. It is designed principally for forest land owners, foresters and managers of both private and public forests who are seeking either to evaluate the productive capacity of their lands, to make short term growth predictions or to make long term working plans for large tracts.

INTRODUCTION

Every forest manager needs to know the volume of wood products his forest can produce. An accurate estimate of future growth is as essential for a forester cutting his stands for continuous production as is a good timber cruise of present volume.

Techniques of estimating growth of ponderosa pine that seemed adequate a decade ago have been antiquated by sweeping changes in the methods of logging that have taken place. Transition from horse and railroad logging to tractor and truck logging, with its characteristic flexibility and lowering of costs, has enabled pine foresters to realize the selectivity in timber marking that they had long wished were economically feasible. As a consequence of this evolution in logging methods, the formerly prevalent heavy selection cutting of 75 to 85 percent of the virgin stand has been replaced by highly variable, light selection cutting on lands being managed for sustained production. Under present practices, as little as 10 or 15 percent to as much as about 65 percent of virgin stand volume may be removed in highly selective fashion. The residual stands being left for future harvest are heavier, and they are far more variable than formerly.

Resulting from these recent developments has come the need for information on the various factors that affect growth and for a method of appraising and combining all these factors in order to make reliable growth predictions. The method that has been developed and is described herein is new as applied to pine growth, but employs the details of tree, stand and site classification with which pine foresters are fully familiar. The fore part of this paper describes and evaluates the factors that affect growth and mortality. The later pages are devoted to describing a method of calculating growth for specific stands.

For simplicity the elements of stand growth are classified into three categories, and the major factors that have been found to affect each are considered separately:

(1) Gross growth of the saw-timber stand, i.e., the increase in volume due to the growth of merchantable-sized trees, which are defined as trees 12 inches and over outside bark at breast height.

(2) Gross growth of the pole stand, the "in-growth" or the increase in volume due to the passing of small trees into the merchantable-size class, including that due to their subsequent increase in volume.

(3) Tree mortality, or the volume in merchantable-sized trees lost through normal mortality by insects, windfall, suppression, and other natural causes.

It is evident that net growth, or change in timber volume, is simply the sum of the first two quantities, less the third.

FACTORS THAT AFFECT GROWTH OF THE SAW-TIMBER STAND

Tree Class

Growth rates of living organisms always vary with their age and vigor. These two fundamental variables form the basis of the Keen tree classification (5), which was developed several years ago as a means for estimating the growth potentialities and mortality probabilities of individual ponderosa pine trees. This tree classification, named for its author, F. P. Keen, is now widely used in the ponderosa pine forests of Oregon and Washington for timber marking and for mortality and growth studies, and has been adopted in modified form in other parts of the ponderosa pine region.

Under this system, individual trees are grouped into four age classes, namely, young, immature, mature, and overmature, designated respectively by numbers 1, 2, 3, and 4, and into four crown-vigor classes defined as full vigor, good to fair, fair to poor, and very poor. Vigor classes are designated respectively by the letters A, B, C, and D. Under this classification of 16 groups a young tree of full vigor is termed a 1A, a mature tree of very poor vigor a 3D, etc.

Detailed definitions of the four classes, designed especially to fit the prevailing forest site class of central and southern Oregon and northern California, namely site IV, are presented in parallel columns in table 1.4/ Similarly the four crown-vigor classes are presented in table 2.4/ These classes are shown pictorially in figure 1.

4/ These tables are copied directly from a mimeographed manuscript by F. P. Keen, entitled "Ponderosa Pine Tree Classes Redefined," October 1, 1942, and correspond closely to the text in the Journal of Forestry article of the same title cited above.

TABLE 1.--AGE CLASSES--(AFTER KEEN)

Character	Class 1	Class 2	Class 3	Class 4
Maturity:	Young	Immature	Mature	Overmature
Age:	Usually less than 80 years	Approximately 80 to 180 years	Approximately 180 to 300 years	More than 300 years
D.b.h.:	Rarely over 20 inches	Rarely over 30 inches	Rarely over 40 inches	Usually large diameters in dominant trees.
Height:	In lower canopy usually less than 60% of total height of mature canopy	Height usually less than 90% of total height of mature canopy	Height practically that of general crown canopy (except of intermediate, suppressed or topkilled trees)	Full height of general canopy (except suppressed spike-topped or broken trees)
Growth and taper:	Thrifty trees making rapid height and diameter growth. Rapid taper	Considerable height growth still in progress; good diameter growth in thrifty trees. Taper considerable	Height growth practically complete; diameter growth slow. Moderate taper	Making no height growth; diameter growth very slow. Least taper
Bark color:	Dark grayish brown to black (except at extreme base)	Dark reddish brown on lower half of bole; dark bark on upper half	Light reddish brown on lower three-fourths of bole; dark bark showing in upper one-fourth of bole	Light yellow; uniform color throughout bole (except at extreme top)
Bark plates:	No plates. Rough bark, deeply furrowed, with narrow ridges between fissures	Narrow smooth plates between fissures	Moderately large plates between fissures	Plates usually very wide, long, and smooth; fissures often rather shallow
Branches:	Branches upturned in upper three-fourths of crown; small for diameter of bole	Mostly upturned in upper half of crown; lower half horizontal or drooping; small to medium for diameter of bole	Upturned near top; middle horizontal; lower ones drooping; moderate for size of bole	Large, heavy limbs, often gnarled or crooked; mostly drooping, except in extreme top
Whorls:	Whorls distinct in upper crown	Whorls distinct in upper half of crown	Whorls indistinct except at extreme top of crown	Whorls indistinct and incomplete
Top:	Top usually pointed	Top usually pointed, sometimes rounded	Top usually pyramidal or rounded, sometimes pointed	Usually flat, occasionally rounded or irregular

Note: Description primarily applicable to central and southern Oregon and northern California, Site IV

TABLE 2.--CROWN-VIGOR CLASSES--(AFTER KEEN)

Character	Class A	Class B	Class C	Class D
Crown vigor:	Full, vigorous	Good to fair	Fair to poor	Very poor
Crown length:	Long, 55% or more of total height; or less only if more than average width	Average length, less than 55% of total height (approximately 30% to 55% if full and wide) or a longer crown if narrow or somewhat thin	Short (from 10% to 30% of height, if crown of normal density) or long, sparse, and narrow	Very short (less than 10% of total height) sometimes merely a tuft at top of tree, or somewhat longer when sparse and ragged
Crown width:	Usually average width or wider (narrower if very long and dense)	Usually average width or narrower; may be flat on one side	Usually narrow or flat on one or more sides	Usually very narrow and sparse, or limbs all on one side
Crown density:	Usually full and dense or of medium density if longer than 55%	Usually of full to medium density, not sparse or ragged	Often sparse and ragged except at very top	Sparse and ragged
Foliage:	Needles of average length or longer, usually dense and thrifty	Needles of average length, usually dense and thrifty	Needles often short and thinly distributed, but of normal length and density when confined to top one-third of crown	Needles often short; foliage sparse or scattered or only partially developed, but of normal length if reduced in quantity
Position:	Usually isolated or dominant, rarely codominant	Usually codominant; sometimes isolated or dominant; rarely intermediate	Usually intermediate; sometimes codominant or suppressed, but rarely isolated or dominant	Usually suppressed or intermediate, but may occupy other positions if greatly reduced in vigor
Diameter:	Large for age	Average or above for age	Usually below average for age; sometimes larger in decadent trees	Decidedly subnormal for age, but very old, decadent trees may be of large diameter

Note: The descriptions apply to the usual types of trees found in each class; where exceptions occur, the size of living crown and amount of foliage are the primary considerations in determining the vigor class.

FIG. 1

A PONDEROSA PINE TREE CLASSIFICATION

BASED ON AGE AND VIGOR

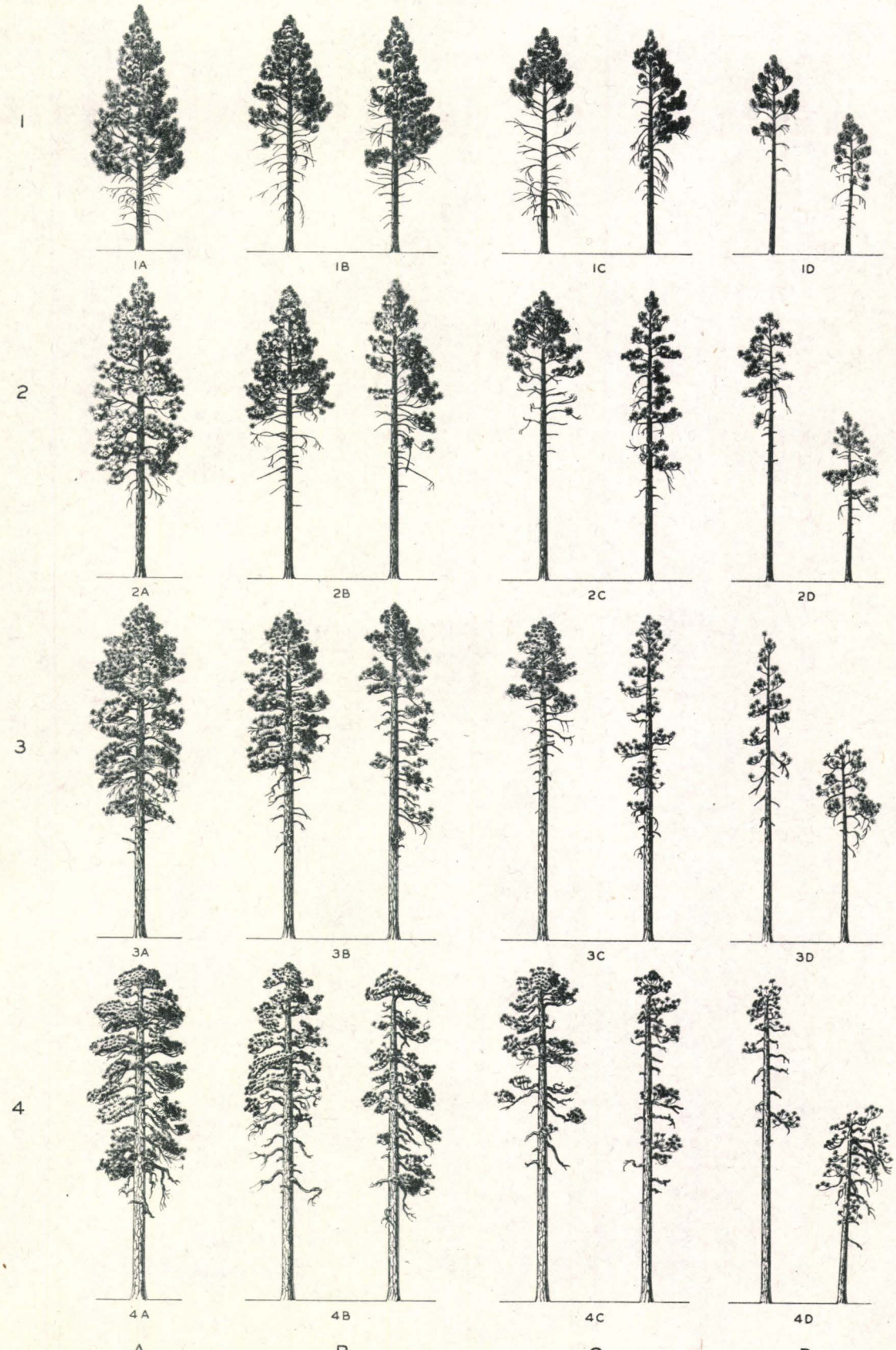
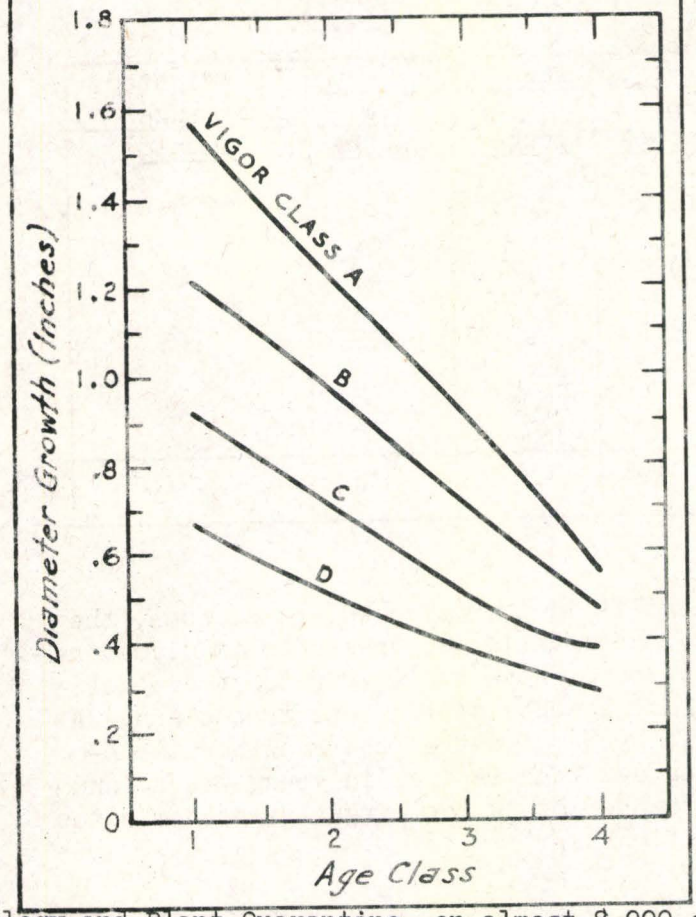


Fig. 2
Normal 10-year Growth in D.B.H., Outside Bark, by Tree Class



Analysis of comprehensive growth data (2), (7) collected from virgin stands by Keen shows that growth rate is strongly and significantly related to tree class. For example, the average diameter growth of all trees in the virgin stand is about three-quarters of an inch per decade. The youngest, most vigorous trees in the stand, the 1A's, make double the average growth, or about 1½ inches in 10 years. In contrast, the oldest, least vigorous trees, the 4D's, grow only about one-quarter of an inch per decade. As shown in figure 2 and table 3, there is a strikingly symmetrical relationship between average diameter growth rates for the various classes. These growth rates for North Pacific ponderosa pine by Keen tree class are based on increment core and other measurements made by the Portland Forest Insect Laboratory, Bureau of Entomology and Plant Quarantine, on almost 8,000 sample trees on 30 10-acre permanent sample plots located throughout the virgin forests of eastern and central Oregon. Although the plots are all located in Oregon, comparative growth data from other sources indicate the findings on them are generally applicable in central and eastern Washington also.

Diameter Within Tree Classes

Within some of the tree classes the normal diameter growth rates vary considerably, depending on tree diameter, as evident in table 4. For the young and vigorous trees, i.e., tree classes 1A, 1B, 2A and 2B, normal diameter growth dimishes as tree size increases. The larger trees, in general, are the older trees, and they grow less rapidly than do the smaller, younger individuals of the same class. At this early stage of tree development the decrease of growth rate with increasing age is sufficient to overbalance the opposite tendency for larger trees to be more vigorous than the smaller ones in the same age class.

Table 3.--Normal 10-year Growth in Diameter at Breast Height Outside Bark, by Tree Class in Virgin Forests

Age class	Vigor class				Unweighted average
	A	B	C	D	
	Inches	Inches	Inches	Inches	Inches
1	1.56	1.21	.92	.66	1.09
2	1.21	.97	.71	.49	.84
3	.90	.71	.50	.37	.62
4	.55	.46	.37	.27	.41
Unweighted average	1.06	.84	.62	.45	.74

For trees of good thrift in the advanced age classes, the 3A's, 3B's, 4A's, and 4B's, the relation of tree size to diameter growth rate is quite the reverse. Here the larger trees are definitely more vigorous than smaller ones of the same tree class. At this later stage in the life cycle of a tree the growth rate decreases less with increasing age than it does in young trees, and the effect of greater vigor inherent in the larger sizes dominates the diameter-age-vigor relationship.

In all C-vigor classes, trees of fair to poor thrift, diameter growth rate is independent of tree size. Although the larger trees in these classes are older than their class average, there is a compensating tendency for such trees to be more vigorous than ones of equal age.

The D-crown trees, those of very poor vigor, in all age classes consistently show a decline in diameter growth with increase in size, a trend that might logically be associated with increasing age and increasing competition with more vigorous stand associates.

Tree diameter increment consists of the combined growth of wood and bark. For trees of normal to rapid growth, increase in bark thickness comprises about 6 percent of the total diameter increment. Trees of abnormally low vigor, however, may occasionally suffer an actual decrease in diameter outside bark, even while diameter of the wood increases slightly, owing to the loss of bark by sloughing.

PLATE I. A giant ponderosa pine tree, 8½ feet in diameter, near the Pringle Falls Experimental Forest in central Oregon,--an extreme example of a 4A tree.

Table 4.--Normal 10-year Growth in Diameter at Breast Height Outside Bark by Tree Class and Diameter Class in Virgin Forests

Diam. at B.H.	Tree class				Tree class				Tree class				Tree class				Diam. at B. H.
	1A	1B	1C	1D	2A	2B	2C	2D	3A	3B	3C	3D	4A	4B	4C	4D	
In.		Inches				Inches				Inches				Inches			In.
10	1.69	1.28	.92	.66	1.50	1.14	.71	.49			.50	.41				.32	10
12	1.60	1.21	.92	.64	1.42	1.07	.71	.49			.50	.39				.31	12
14	1.51	1.13	.92	.63	1.34	1.01	.71	.47		.57	.50	.38			.37	.30	14
16	1.42	1.06	.92	.61	1.28	.97	.71	.46	.73	.60	.50	.36			.37	.29	16
18	1.33	.99	.92		1.23	.93	.71	.45	.76	.64	.50	.34		.38	.37	.28	18
20	1.24	.93			1.16	.90	.71	.44	.80	.66	.50	.33		.39	.37	.27	20
22	1.15				1.13	.88	.71		.83	.68	.50	.31		.41	.37	.26	22
24					1.11	.86	.71		.86	.70	.50	.29	.48	.42	.37	.25	24
26					1.09	.84	.71		.88	.72	.50	.28	.50	.43	.37	.25	26
28					1.08	.83			.90	.74	.50	.26	.51	.45	.37	.24	28
30					1.06	.82			.92	.76	.50	.24	.52	.46	.37	.23	30
32					1.04				.94	.77	.50		.54	.46	.37	.22	32
34									.96	.78	.50		.55	.47	.37	.21	34
36									.97	.79	.50		.56	.48	.37	.20	36
38									.99	.79	.50		.57	.49	.37	.19	38
40									1.00	.80			.58	.50	.37	.19	40
42									1.01	.81			.59	.50	.37		42
44									1.02	.81			.59	.51	.37		44
46									1.02				.60	.51	.37		46
48													.60	.52	.37		48
50													.61	.52			50
54													.62				54
58													.62				58

This is evident from the following equation that expresses the multiple relationship between bark thickness and tree diameter, tree age, and tree vigor:

> Double bark thickness at breast height in inches = .0787 d.b.h.,o.b. - .1615 age class - .1235 vigor class + 1.981 when, for convenience, vigor classes are given the numerical values of 1, 2, 3, and 4 for vigor classes A, B, C, and D, respectively.

In Appendix B there is more detailed discussion of the relation of bark thickness to diameter increment.

Volume growth rate is even more variable than diameter growth. Individual ponderosa pine trees growing in an average virgin stand may be expected to put on a gross volume increment of anywhere from 6 to 177 board feet per decade, depending on their size, age, and vigor. From table 5, which gives normal 10-year volume growth, it is evident that trees of identical diameter may grow at widely varying rates--increment is much greater the younger the age and the better the vigor. Within any one tree class the board-foot volume growth rate increases with tree size, as would be expected.

Volume growth percent, or growth as a percentage of the volume to which it is added, is an expression of increment frequently found convenient. It is the measure of tree growth most commonly employed, along with mortality probability and tree value, in drawing up marking rules to be applied in selective cutting. As indicated in table 6, the gross annual growth of virgin ponderosa pines ranges from .12 to 7.93 percent of their board-foot volume, depending on tree size, age, and vigor. For trees of the same size, growth percent is greater the younger the age and the better the vigor, without exception. Within any one tree class, growth percent is smaller the greater the diameter, also without exception.

Site Quality

The rate at which any class of tree grows depends in large part upon the soil and climatic conditions of the area upon which it is situated. Thus the relative productive capacity of a given forest area, determined by the combined factors of climate, topography, and soil, is referred to as its site quality. Seven site-quality classes are recognized throughout the range of ponderosa pine. They are designated by Roman numerals I, II, III, etc. Highest quality of site, that on which the tree growth is fastest, is quality class I, the lowest is class VII.

Table 5.--Normal 10-year Gross Volume Growth in Board Feet Per Tree by Tree Class and Diameter Class in Virgin Forests

Diam. at B. H.	Tree class				Tree class				Tree class				Tree class				Diam. at B. H.
	1A	1B	1C	1D	2A	2B	2C	2D	3A	3B	3C	3D	4A	4B	4C	4D	
In.							Board Feet, Scribner Rule										In.
12	38	28	22	15	25	19	15	11			12	9				6	12
14	49	36	30	21	39	30	22	16		20	16	12			10	9	14
16	56	43	37	25	48	37	27	18	31	27	20	15			14	12	16
18	66	50	45		58	45	34	22	40	34	25	17		19	16	14	18
20	75	57			68	52	40	24	50	42	31	19		24	19	16	20
22	83				76	58	46		60	51	37	22		30	22	18	22
24					85	65	54		71	58	43	24	41	36	26	19	24
26					93	70	60		82	66	48	27	48	43	30	20	26
28					100	76			92	74	55	30	57	51	34	21	28
30					106	83			102	81	61	33	65	58	40	24	30
32					111				108	89	67		70	64	44	25	32
34									119	99	73		75	68	46	26	34
36									129	108	78		81	72	51	28	36
38									138	114	85		85	75	56	31	38
40									150	120			88	79	57	33	40
42									162	122			92	82	61		42
44									168	128			94	84	64		44
46									177				96	85	66		46
48													102	86	69		48
50													112	89			50
54													125				54
58													144				58

Table 6.--Normal Annual Gross Volume Growth as Percent of Board-foot Volume by Tree Class and Diameter Class in Virgin Forests

Diam. at B. H.	Tree class				Tree class				Tree class				Tree class				Diam. at B. H.
	1A	1B	1C	1D	2A	2B	2C	2D	3A	3B	3C	3D	4A	4B	4C	4D	
In.		Percent				Percent				Percent				Percent			In.
12	7.93	5.85	4.50	3.15	5.25	4.05	3.10	2.30			1.97	1.52				1.00	12
14	4.85	3.57	2.94	2.02	3.80	2.90	2.14	1.55		1.78	1.45	1.12			.95	.81	14
16	3.38	2.62	2.25	1.49	2.88	2.24	1.66	1.12	1.75	1.50	1.14	.84			.77	.67	16
18	2.63	2.00	1.80		2.33	1.79	1.35	.86	1.51	1.29	.95	.65		.73	.61	.54	18
20	2.14	1.62			1.94	1.49	1.14	.70	1.32	1.13	.83	.52		.65	.51	.43	20
22	1.78				1.64	1.25	1.00		1.18	1.00	.73	.43		.59	.44	.35	22
24					1.40	1.06	.88		1.06	.88	.65	.37	.62	.55	.39	.28	24
26					1.21	.91	.78		.96	.78	.57	.32	.57	.51	.35	.23	26
28					1.05	.80			.86	.69	.51	.28	.53	.48	.32	.20	28
30					.92	.72			.78	.62	.46	.25	.49	.44	.30	.18	30
32					.82				.71	.57	.43		.45	.41	.28	.16	32
34									.66	.52	.40		.41	.37	.25	.14	34
36									.61	.48	.37		.38	.34	.24	.13	36
38									.58	.45	.35		.35	.31	.23	.13	38
40									.55	.43			.32	.29	.21	.12	40
42									.52	.41			.30	.27	.20		42
44									.50	.39			.28	.25	.19		44
46									.48				.26	.23	.18		46
48													.25	.21	.17		48
50													.25	.20			50
54													.24				54
58													.24				58

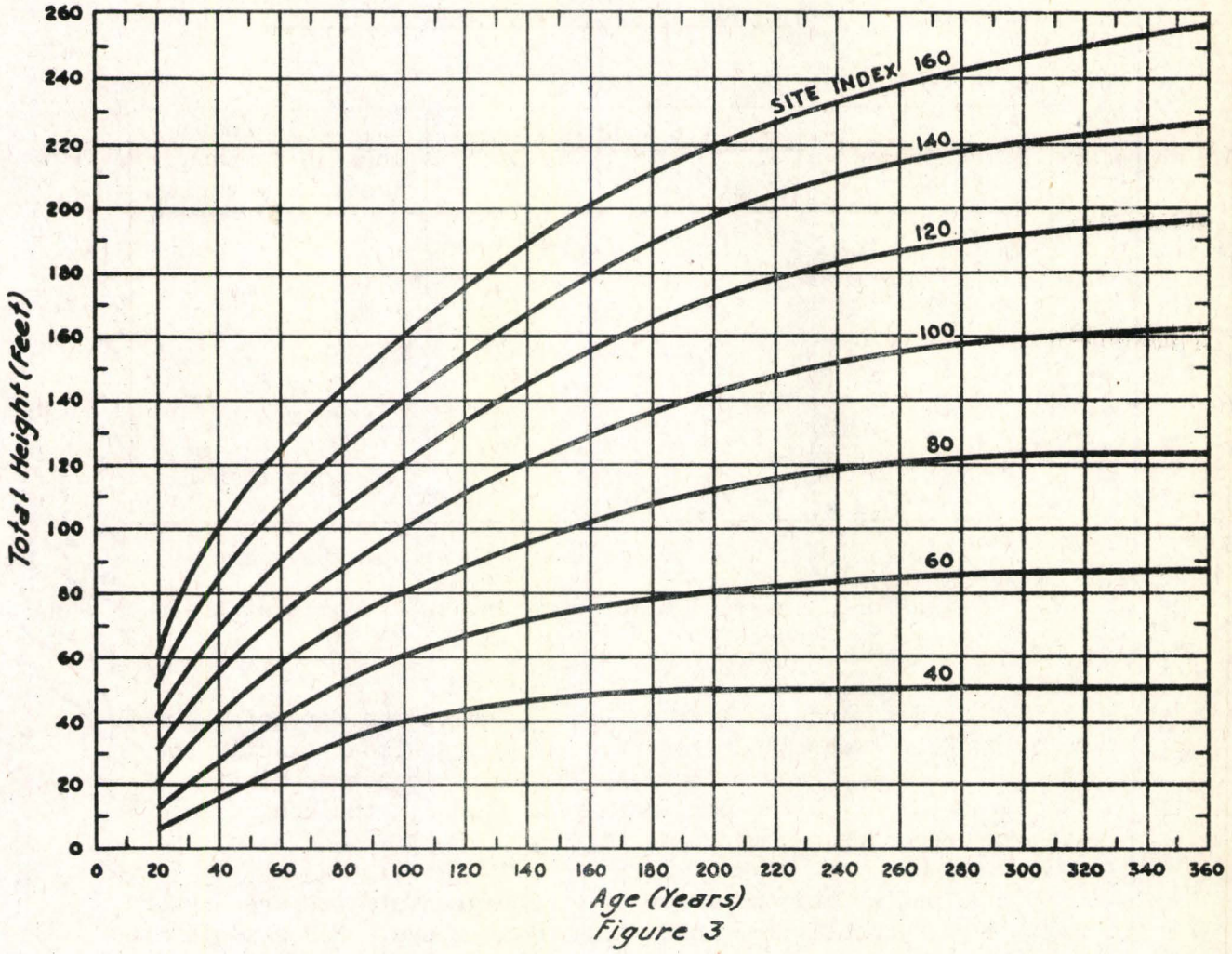


Figure 3

Height of Dominant and Codominant Trees of Average Breast-high Diameter

The index of site employed is the height in feet of average-diameter dominant and codominant trees at age 100 years. For example, "site index 80" for a given area means that the dominant and codominant trees upon it average, have averaged, or will average 80 feet in height at 100 years of age. The site classification employed in the present study is that described in U.S. Department of Agriculture Technical Bulletin No. 630, "Yields of Even-aged Stands of Ponderosa Pine," by Walter H. Meyer, 1938 (9). Significance of site quality class in terms of site index units and in 16-foot logs to an 8-inch top in dominant trees at maturity is shown in table 7 taken from the above publication. Figure 3 (also from Tech. Bul. 630) (9) shows height of dominant and codominant trees of average diameter by age and by site index class.

Table 7.--Site-quality Classification for Ponderosa Pine, with Corresponding Heights at Maturity[1] in Terms of Number of Logs in Dominant Trees

Site-quality class	Site Index[2]		No. of 16-foot logs in dominant trees at maturity
	Central value	Range	
	Feet	Feet	
I	120	113+	10 or more
II	106	99 - 112	8 or 9
III	92	85 - 98	7
IV	78	71 - 84	5 or 6
V	64	57 - 70	3 or 4
VI	50	43 - 56	2
VII	36	43 -	Less than 2

1/ Maturity is assumed to begin at the age of 250 years.

2/ Height of average diameter dominant and codominant trees at age 100 years.

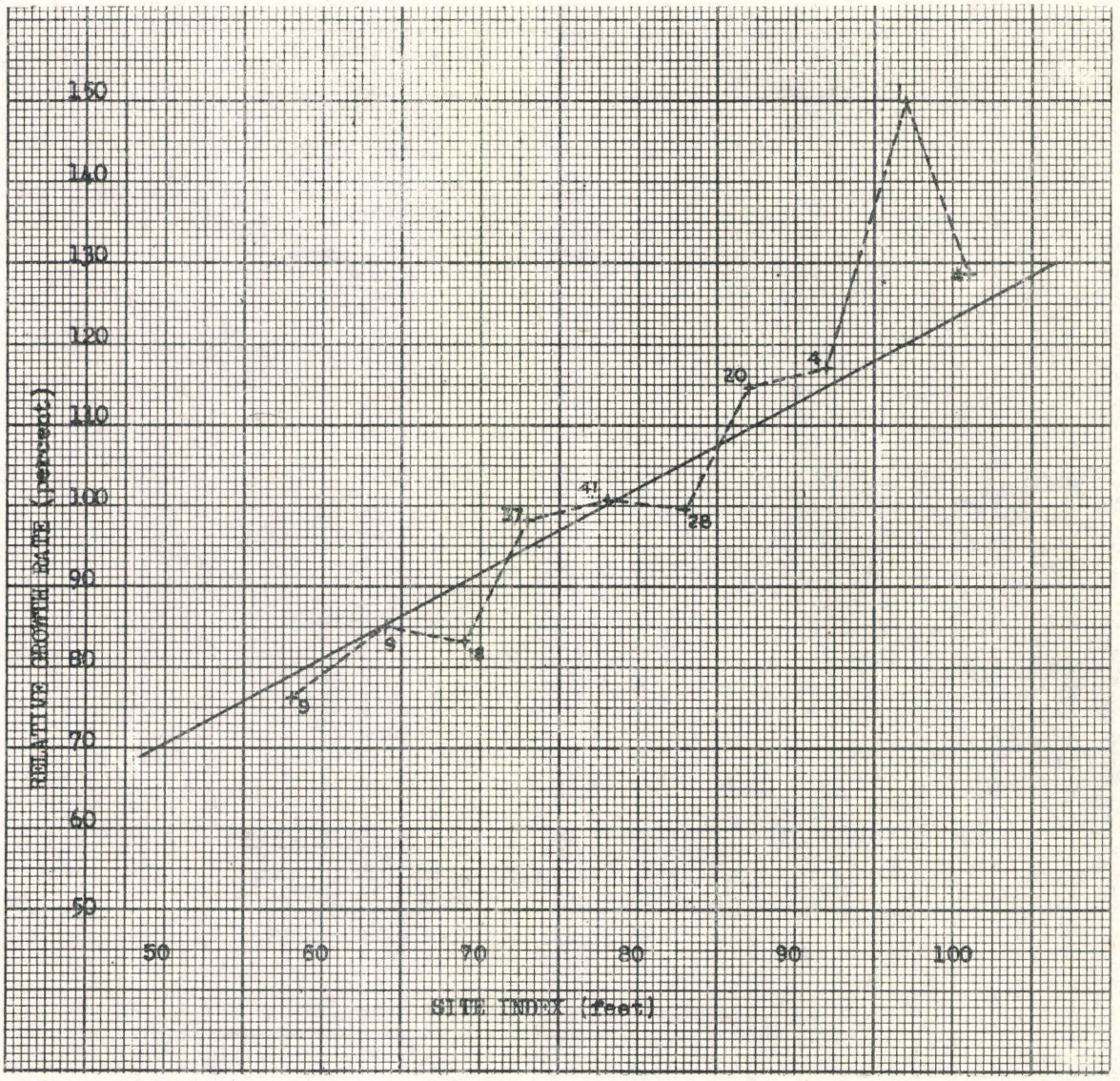
The site index of the plots, for which the foregoing growth rates by Keen tree class are given, averages almost exactly the central value of class IV, namely 77. This is representative of about two-thirds of the ponderosa pine lands in the central and eastern Oregon-Washington pine region.

On better and on poorer sites the growth rates are higher and lower, respectively, than those given above. For example, the normal rates of diameter growth on site III lands are 10 percent greater than those shown in tables 3 and 4 for site IV. Rates on site V are 10 percent less than those tabulated.

The most satisfactory expression of the effect of site on volume growth of ponderosa pine trees in many aged stands has been derived by reanalysis of the data upon which Technical Bulletin 407 (8) was based. These data consist of increment borings and other measurements on 179 temporary sample plots located throughout the ponderosa pine region of Oregon and Washington. The plots, which averaged about 1.8 acres in area, ranged from class II to class V in site quality.

Result of this reanalysis is shown in figure 4 and table 8. Adjustment of the foregoing volume growth rates for site differences is simple. If it is desired to adapt volume growth rates to site-quality class III, figures in table 5 or 6 are multiplied by 1.15; for site-quality class V by .86.

Figure 4. Net effect of site index on rate of volume growth.



Area of forest land in each of the ponderosa pine site quality classes in central and eastern Oregon and Washington as found by the Forest Survey (3) is given in table 9.

Stand Competition

Growth of an individual tree depends not only on its own age, vigor, size and on the productive capacity of its site, but it is also influenced by the number, the size, proximity, and competitive ability of its neighbors. A most significant quantitative measure of this effect also has been obtained by the recent reanalysis of the basic data collected by Meyer for the preparation of Tech. Bul. 407 (8).

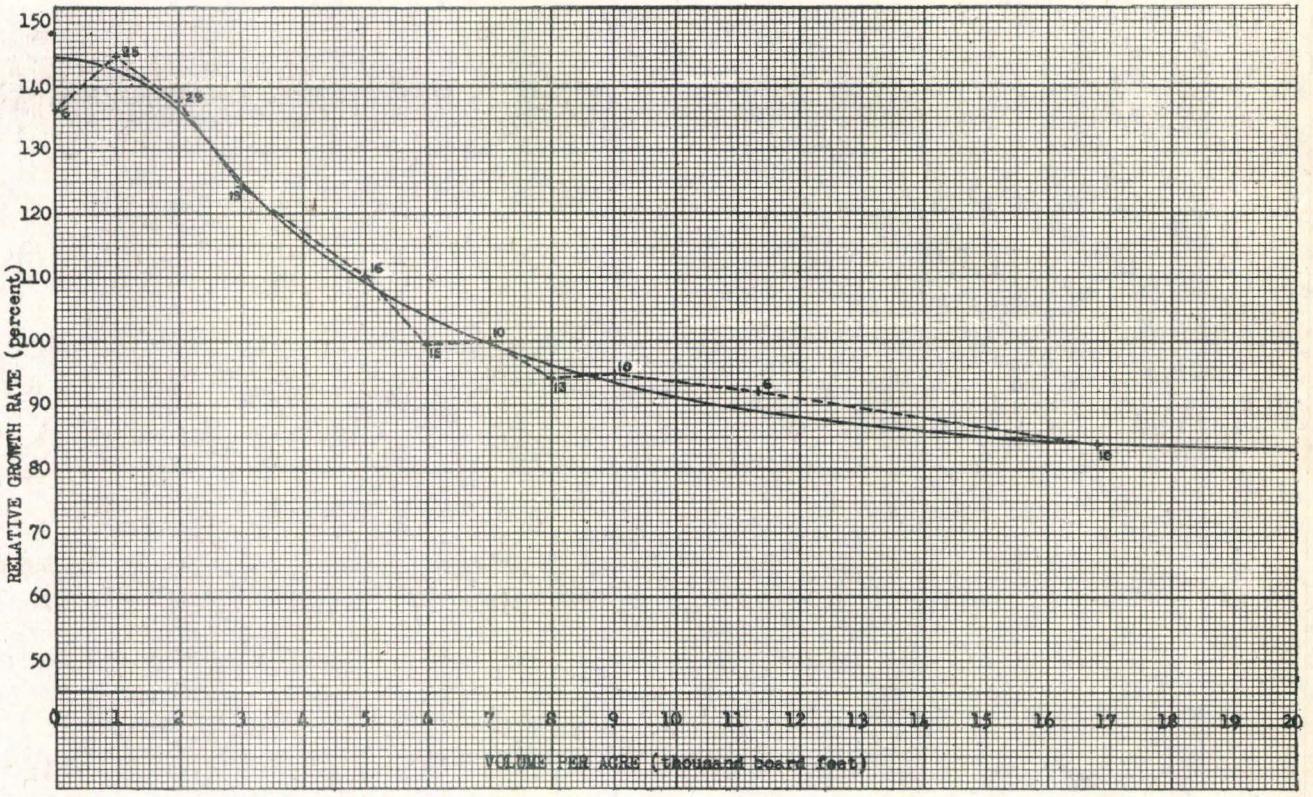
Table 8.--Correction for Effect of Site on Board-Foot Volume Growth Rates

Site index	Site quality	Correction factor
Feet	Class	Percent
50	VI	71
60		82
64	V	86
70		92
78	IV	101
80		103
90		113
92	III	115
100		124
106	II	130
110		135

Table 9.--Land Areas of Ponderosa Pine Sites in the Ponderosa Pine Region of Washington and Oregon, by Site-quality Class, 1936

Site-quality class	Land area
	Acres
I	480
II	18,018
III	711,604
IV	7,849,633
V	3,193,731
VI	268,801
Total	12,042,267

Figure 5. Net effect of total stand volume per acre on growth rate of individual trees.



The two expressions of stand competition found most useful in measuring effect on growth are total volume per acre, and, in the case of selectively cut stands, the percent of virgin stand volume reserved for future growth. Influence of total stand volume per acre on the growth rate of trees within that stand is shown graphically in figure 5. It is evident that a tree's growth rate is smaller the heavier the timber stand in which it is situated. Growth does not decrease at a uniform rate, however, for each additional unit of volume. Up to about 2,000 board feet per acre the reduction is slight, indicating that, on the average, trees in such light stands do not benefit much from additional space. In heavier stands, the reduction in growth for each added unit of volume becomes substantial, but the effect of each added unit is less than that of the previous one until in stands of about 9,000 board feet or greater, the influence of additional volume is comparatively small.

Net effect on growth rate of individual trees in percent of virgin stand volume reserved is shown in figure 6. The greater the percentage reserve, the smaller is the relative growth rate, but the reduction is at a diminishing rate as additional percentages are added.

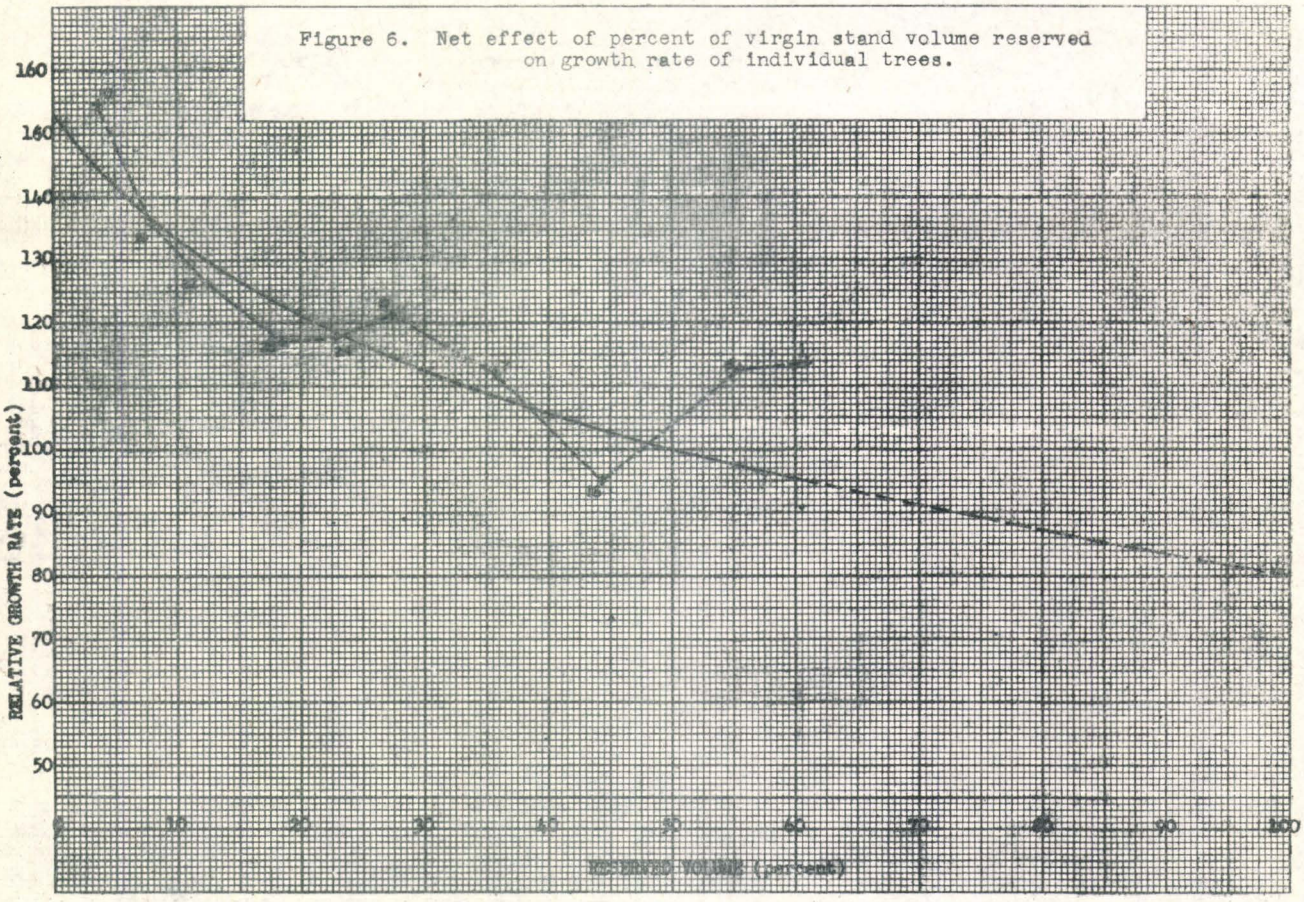


Figure 6. Net effect of percent of virgin stand volume reserved on growth rate of individual trees.

The combined effect of these two factors, related to the volume growth rates by Keen tree class in tables 5 and 6, is given in table 10. Stands in which the rates by Keen class were measured averaged about 16,000 board feet per acre, and since no cutting had ever been done in them, they represented 100 percent reserve. In heavier virgin stands the growth rates per tree are only slightly less than those tabulated; in lighter virgin stands they average somewhat greater. In this connection it is important to remember that volumes per acre are based on timbered area only. Area of all openings or breaks in the forest cover of about $\frac{1}{4}$-acre or larger should be excluded in computing volume per acre.

Allowance for effect of stand competition represented by total volume and percent of virgin stand volume reserved is easily made by reference to the table. Assume, for example, a stand of 8,000 board feet per acre remains after taking a 50 percent cut from a virgin forest of 16,000 per acre. The volume growth rates of trees remaining in such a stand are expected to average, according to table 10, 30 percent greater than the rates shown in tables 5 and 6.

Table 10.--Correction for Effect of Stand Competition, as Expressed by Reserve Volume Per Acre, and Percent of Original Volume Reserved, on Board-Foot Growth Rates

Reserve volume per acre	PERCENT OF ORIGINAL VOLUME RESERVED												
	0	5	10	15	20	30	40	50	60	70	80	90	100
M bd.ft.	Correction factor (percent)												
0	232												
1	229	217	209	203	196	188							
2		211	203	197	191	182	176	171	165				
3			191	186	179	171	164	158	153	149	145		
4			182	177	170	161	155	150	145	141	137	134	131
5				170	163	155	148	142	137	134	130	126	124
6				165	158	150	143	137	132	129	125	121	118
7					154	146	139	133	128	125	121	117	114
8					151	142	136	130	125	121	117	114	111
9						139	133	127	122	118	115	112	109
10						137	131	125	120	116	113	110	107
12							127	122	117	113	110	106	103
14							125	120	115	111	108	104	101
16								119	114	110	106	102	100
20								117	112	108	105	101	98
24									111	107	104	100	97

Timber cutting that tends to be groupwise and leaves a reserve stand of strongly competing trees in tight groups interspersed by clear-cut openings cannot be expected to result in the degree of release indicated in table 10. On the other hand, achievement of good spacing in the reserve stand by care during timber marking should result in better than indicated release. This is due to the fact that table 10 is based on measurements of accelerated growth that occurred, for the most part, in stands that were cut over years ago without conscious regard to the best forestry principles.

An interesting and logical deduction from table 10 is that a given reserve stand volume does not represent uniform stand competition conditions. Reference to the table indicates that trees in a 5,000-board-foot-per-acre stand representing a 20 percent reserve from a 25,000 original are expected to grow 63 percent more rapidly than shown by the normal tree class growth rates. If, however, the 5,000-foot stand represents a 70 percent reserve from an original of 7,150 board feet, it is expected to grow only 34 percent more rapidly than indicated by the tabular tree class rates. In the first case the residual stand was released by removal of 20,000 board feet, in the second by removal of only 2,150. In such stands as the second, spacing, on the average, is poorer than in such stands as the first.

In mixed stands, it is important that all species be considered when computing total stand volume and percent reserve for use as indices of stand competition.

A convenient means of making a single combined correction of growth rates, given in tables 5 and 6 for effect of site, reserve volume, and percent reserve, is shown in figure 7. Assume, for example, a residual stand of 7,000 board feet per acre, representing a 50 percent reserve from an original 14,000 growing on land of site index 85. In figure 7 span with a straight edge from 85 on the X_1-axis to 50 on the X_2-axis and hold the intersection on the S-axis. From this intersection, span to 7 on the X_3-axis and read the indicated correction intersected on the Y-axis: 142 percent.

A number of attempts have been made to express stand competition in terms of tree distribution or spacing, but to date, no such adequate numerical measure has been found. One such proposed measure worthy of further study is the coefficient of variation[5/] of stand volume by small plots. Reanalysis of all the plots used by Meyer revealed an average coefficient of variation based on $\frac{1}{4}$-acre units of 70 percent of the mean. Stands having a coefficient of variations of less than average, indicating more uniform distribution, made slightly greater than average growth. For example, stands for which coefficient of variation was 20 percent averaged 3 percent greater than normal growth. In contrast, those having a coefficient of variation of 160 percent, indicating groupwise distribution, averaged 5 percent below normal in increment. It is believed that this measure, based in smaller unit areas might prove to be significantly related to growth rate.

The amount of understory saplings and brush may also affect the growth of the sawtimber stand through competition for soil moisture and nutrients, but quantitative information on this aspect of stand structure is lacking.

Species Composition

The foregoing volume growth rates apply to ponderosa pine growing in pure stands or in mixed stands in which ponderosa is the predominating species. Growth rates of common associates of ponderosa pine, such as Douglas-fir, white fir, western larch, and lodgepole pine, are not known in comparable detail. Preliminary growth estimates for these species can be made best from information available as a result of the Forest Survey (1). The basis is contained in table 11. These rates may be adapted for use on sites other than class IV by use of the correction factors given in table 8. Since comparatively little is known about the ability of the associates of ponderosa pine to respond to release, the stand competition correction factors given in table 10 cannot be applied directly with a desirable degree of confidence. If the cutting leaves the associated species in unreleased groups, no allowance for acceleration of growth should be made. If their spacing is significantly improved, the values in table 10 may serve as a useful basis for estimating what acceleration will occur.

5/ Standard deviation around the mean expressed as percent of the mean.

Figure 7.
Alinement chart for computing corrections for differences in site index and in stand competition in many-aged ponderosa pine forests.

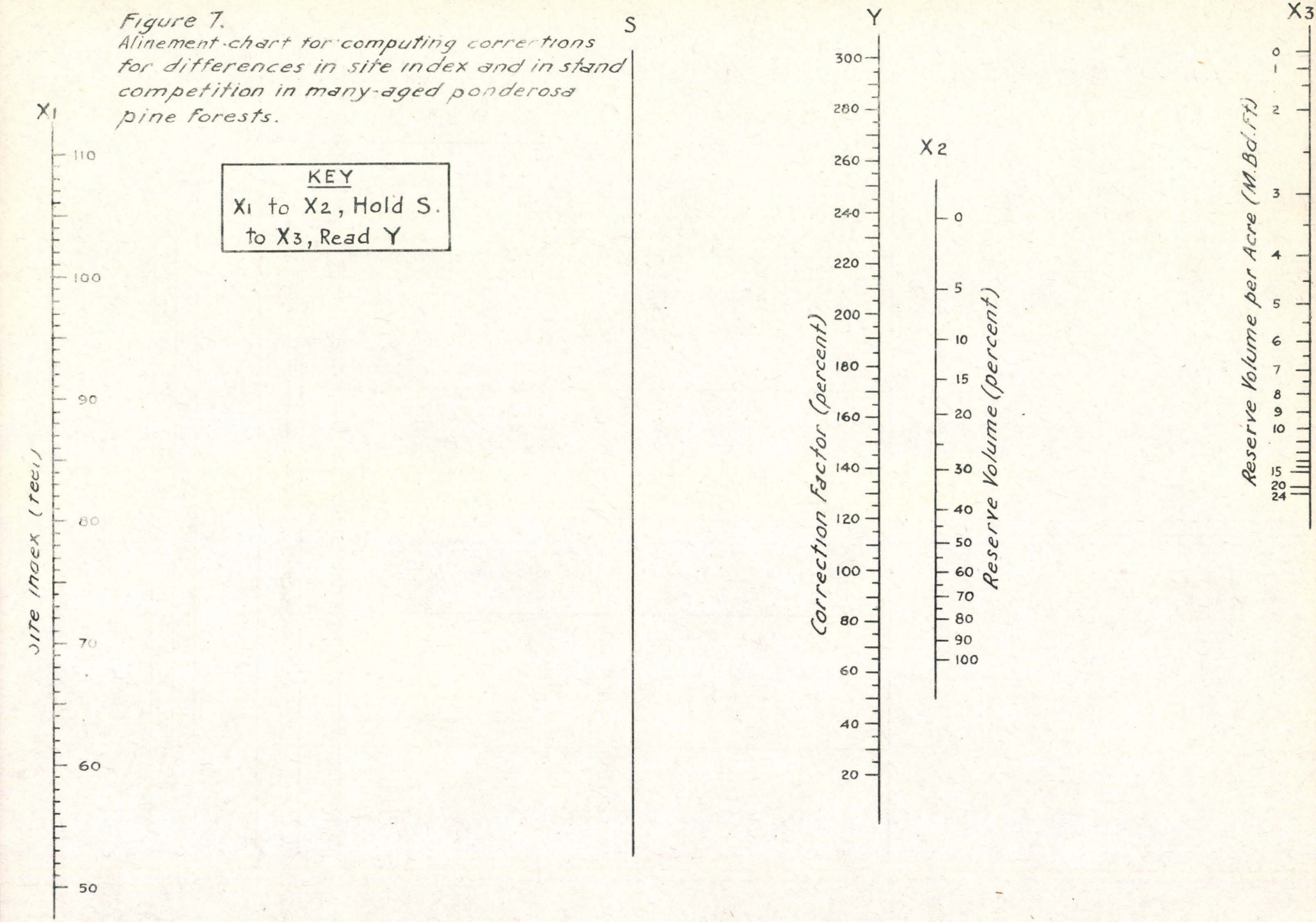


Table 11.--Preliminary Rates of Average Annual Gross Volume Growth Percent for Associated Species in Virgin Ponderosa Pine Stands on Site IV, by D.B.H., Species Group, and Crown Class

D.B.H.	Douglas-fir, white fir, and sugar pine			Western larch and lodgepole pine		
	Dominant & codominant	Intermediate	Suppressed	Dominant & codominant	Intermediate	Suppressed
	Percent					
12	3.50	2.52	1.61	2.92	2.16	1.34
14	2.70	2.00	1.24	2.18	1.61	1.00
16	2.25	1.66	1.04	1.68	1.24	.77
18	1.95	1.44	.90	1.37	1.01	.63
20	1.73	1.28	.80	1.08	.80	.50
22	1.55	1.15	.71	.90	.67	.41
24	1.40	1.04	.64	.75	.56	.34
26	1.26	.93	.58	.64	.47	.29
28	1.16	.86	.53	.56	.41	.26
30	1.07	.79	.49	.49	.36	.23
32	.99	.73		.44	.33	
34	.93	.69		.39	.29	
36	.87	.64		.35	.26	
38	.82	.61		.32	.24	
40	.77	.57		.28	.21	
42	.74			.25		
44	.70			.23		
46	.66			.21		
48	.63			.19		
50	.60			.18		

PLATE II. Above--A selectively cut forest immediately after logging in 1914.

Below--The same scene 20 years later. This forest, in the Blue Mountains of Oregon, was cut selectively to the extent of 82 percent by volume by the system then prevalent on the national forests. Between 1914 and 1939 this stand made an annual gross growth of 72 board feet (Scribner rule) per acre per year and suffered mortality amounting to 33 board feet per acre per year.

Other Factors

Change in Tree Class

One of the obvious generalizations involved in the above method centers around the assumption that all tree classes are affected by release to the same extent. This assumption is contrary to theory and to the findings of preliminary studies, but thus far a practical method of providing separate release factors for the various tree classes has not been devised. This point deserves further study. It is related to the problems of change in tree class with the passage of time, another theory which has not yet been expressed in terms of measurements. These two factors are of comparatively minor importance in the making of growth estimates for stands containing a number of tree classes because compensations are known to occur. However, they are believed to be considerations of some import in judging the comparative desirability for cutting of the various tree classes in the formulation of marking rules.

Length of Growth Period

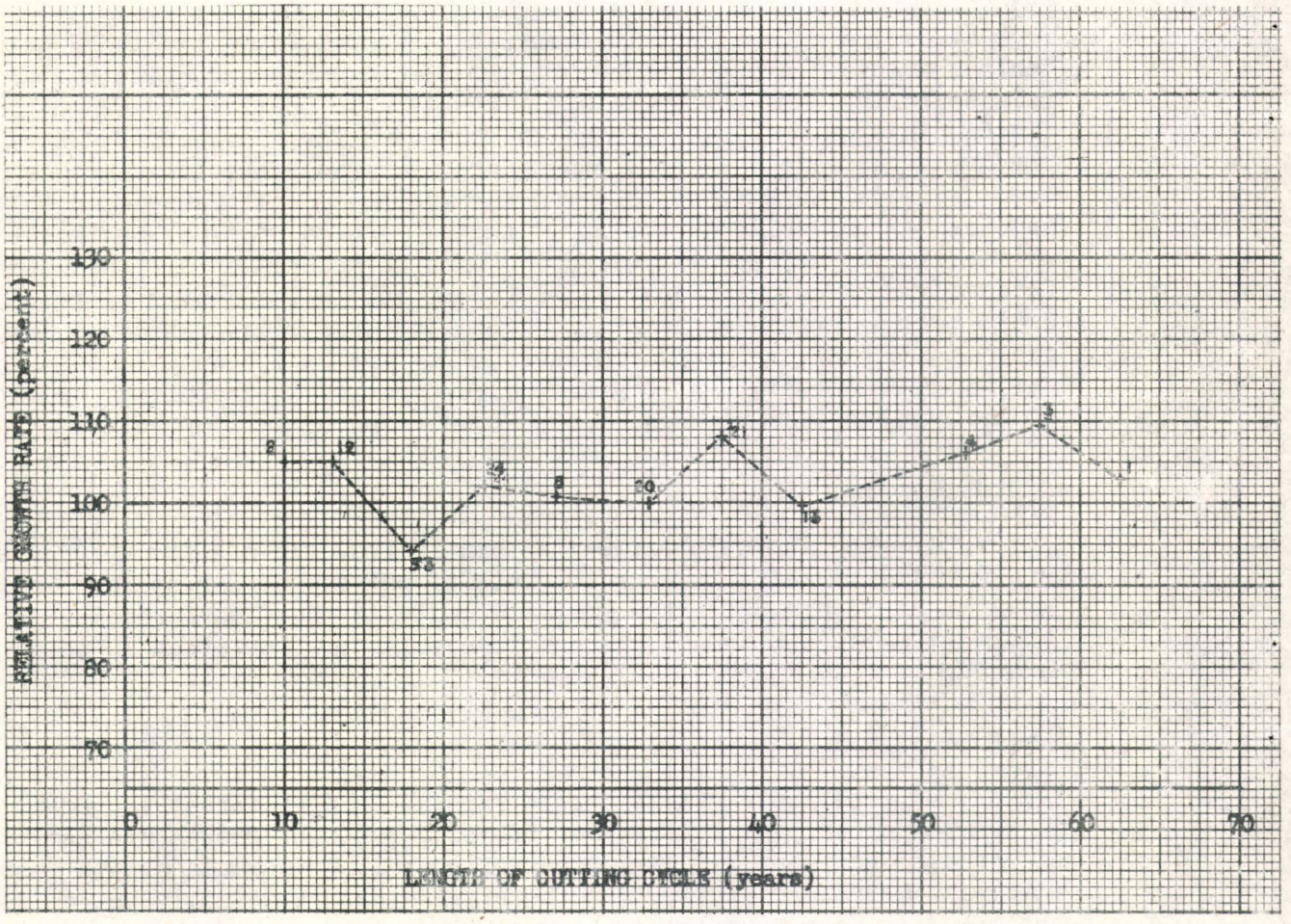
Length of growth period, within limits, was not found to have any considerable effect on growth rate of the saw-timber stand. This is shown in figure 8. Data available indicate that the foregoing growth rates apply reasonably well to cutting cycles of from about 10 to at least 40 years.

Climatic Cycles

Wide periodic variations in rainfall and in forest increment occur in the ponderosa pine belt. The foregoing rates of growth are estimates of average increment during periods of so-called "normal" growth associated with normal rainfall. But the growth that is actually put on during any specific decade or two may surpass or fall short of the expected by a wide margin, perhaps as much as 40 percent, depending on rainfall excess or deficiency, whichever occurs. Fortunately for longer periods these wide discrepancies tend to compensate, and since the length or intensity of a good or poor growth cycle cannot be predicted with accuracy, the best estimate of growth that can be made for any future period is the "normal" rate.

Nevertheless, a knowledge of the effects of climatic cycles is desirable in order to understand the extent of variation that may occur. Poor growth periods do not affect all tree classes to the same degree. This is shown in table 12, based on analysis of data collected by Keen (6), (2). It shows annual diameter growth from 1929 to 1938 (a period of exceptionally poor increment) as percent of that made during

Figure 8. Relation of length of growth period on growth of sawtimber stands.



the years 1900-29, inclusive, a period selected as approximating normal growth. Trees of the low vigor classes suffered a greater relative reduction in growth during the unfavorable period than did the more vigorous trees. Among the A-and B-crown trees the greatest reduction occurred in the older age classes, but among those having C and D crowns the greatest reduction occurred in the younger ages.

The effect of growth cycles is also more pronounced on poor sites than on the good. This logical interrelationship of site and climatic cycle with growth is shown in table 13, which gives the relative diameter growth rates made on site quality classes III, IV, and V during a normal, a severely subnormal, and a supernormal growth period. During the 1929-38 period of slow growth, increment on site IV dropped to 58 percent of its normal rate. Growth on site V fell to 51 percent (46 ÷ 90) of its normal, but that on site III was less

Table 12.--Annual Diameter Growth, 1929-38, as Percent of That Made During the Period 1900-29, by Tree Class

Age class	Vigor class				Weighted average
	A	B	C	D	
	Percent	Percent	Percent	Percent	Percent
1	69.0	66.0	60.6	48.0	62.0
2	65.8	62.3	57.5	47.0	61.4
3	63.5	59.9	56.5	50.5	55.7
4	62.5	60.0	58.9	57.1	59.7
Weighted average	64.4	59.9	56.9	51.2	58.3

Table 13.--Diameter Growth as Percent of That Made On Site IV Lands During Normal Growing Cycle by Site Quality Class for 3 Growth Periods

Site quality class	Growth period		
	Normal (1900-29)	Subnormal (1929-38)	Supernormal (1900-19)
	Percent	Percent	Percent
III	110	71	119
IV	100	58	110
V	90	46	101

drastically reduced to 65 percent of its normal rate. During the 1900-19 period, growth on site IV increased to 10 percent above its normal rate, that on site V, 12 percent, but in site III diameter increment progressed only 8 percent more rapidly than normally.

The effect of site index on diameter growth observed during certain periods of normal, subnormal, and supernormal growth can be determined from the equations in table 14.

Table 14.--Equations for Various Climatic Periods Giving the Comparative Diameter Growth Observed in Virgin Timber on Different Sites

Growth Period	Character of Period	Equations giving diameter growth according to site index
1900-29	Assumed normal	Diameter growth in percentage[1/] =46.403+ .7298 site index
1929-38	Severely subnormal	" =15.390+ 1.5020 site index
1900-19	Slightly supernormal	" =60.034+ .5511 site index

1/ In this case 100 percent for each growth period represents the average for all plots, whose site index averages 77.

Locality

Growth of ponderosa pine stands varies widely between the various portions of the region. As would be expected, most of this variation in growth rate can be accounted for by differences in the factors previously considered, such as volume per acre, site quality, and stand structure. After having made allowance for these conditions, smaller differences still remain.

Table 15 shows measured and expected growth rates on 249 sample plots studied in connection with the growth phase of the forest survey of the ponderosa pine region. All were located in representative random fashion in virgin and pure ponderosa pine stands. The samples, taken in strip form, averaged about 16 acres in area. They consisted of stand tallies by tree class; growth rates by tree class were determined from increment borings. Site was measured in the usual manner.

Table 15.--Comparison of Expected with Measured Growth Rate by Keen's Subdivisions of the Region

Regional Subdivisions		No. of sample plots	Gross annual growth per acre		Difference	
No.	Name		Measured	Expected		
			Bd. ft.	Bd. ft.	Bd. ft.	Percent
1	Spokane	4	52	66	- 14	- 27
2	Colville	15	78	81	- 3	- 4
3	Chelan	16	100	103	- 3	- 3
4	Wenatchee	14	86	89	- 3	- 3
5	Yakima	18	128	122	+ 6	+ 5
6	Klickitat	24	131	114	+ 17	+ 13 1/
7	Lower Deschutes	10	109	107	+ 2	+ 2
8	Upper Deschutes	9	121	113	+ 8	+ 7
9	Klamath Marsh	5	105	103	+ 2	+ 2
10	Klamath Lake	2	195	218	- 23	- 12
11	Sprague River	18	113	113	0	0
12	Lakeview	7	119	128	- 9	- 8
13	Fort Rock	3	74	86	- 12	- 16
14	Ochoco	10	98	106	- 8	- 8
15	Burns	37	78	94	- 16	- 21 1/
16	John Day	44	88	80	+ 8	+ 9 1/
17	Baker	5	112	99	+ 13	+ 12
18	La Grande	8	61	58	+ 3	+ 5

1/ Significant at odds of 20 to 1.

Plots were grouped by 18 broad subdivisions of the ponderosa pine region as delineated by Keen and based principally on climatic, ecological and topographic factors. The "expected" growth rates are those calculated by allowing for differences in volume, site, structure, etc., based on the regional average effect of these variables on growth.

Three of the differences between measured and expected growth are statistically significant: Measured growth in the Klickitat subdivision was 13 percent greater than the expected, that in the John Day was 9 percent greater, and that in the Burns subdivision was 21 percent smaller. Measured growth on the four plots taken in subdivision 1, on the Spokane Indian Reservation, was 27 percent below "expected". This difference, though substantial, is based on too few plots to be statistically significant.

Whether the three significant differences are due to more or less permanent factors, such as climate, soil, or topography, inadequately accounted for in the height-over-age measure of site, or to a comparatively temporary stand condition, is unknown. Cause of the differences, other than their association with locality is not proved.

FACTORS AFFECTING GROWTH OF THE POLE STAND

The increase in volume due to the growth of pole-sized trees into the saw-timber size class or "in-growth", and their additional growth thereafter, may be an important part of total volume increment in a pine forest. (See Plate 3). Growth from this source depends upon the number of poles (trees in the 4-, 6-, 8-, and 10-inch diameter classes) present in the stand, and the growth contributed by each, which in turn depends upon pole size, tree class, and the length of the period over which increment is measured. As shown by table 16, growth per pole may range from 0 to 5 board feet annually, depending on the above variables. During a period as short as 10 years, only a portion of the 10-inch poles, plus some of the 8-inch in the most vigorous tree classes, are expected to grow to saw-timber size, i.e., as herein used, 12 inches or over in diameter. But over a longer period some of the poles in the smaller diameter classes and less vigorous tree classes grow to saw-timber size. The figures in table 16 include the in-growth, i.e. the increment due to the trees that grow into the 12-inch diamter class, plus whatever additional growth they make over the indicated periods of time. These figures were compiled by reanalysis of the data on which Meyer's Technical Bulletin 407 (8) was based.

Further analysis shows clearly that growth contributed by the pole stand is also influenced by site quality and by stand competition in much the same nanner as is growth of the saw-timber stand. Effect of these two factors on pole growth is shown in table 17 and in figure 9. For example, growth of a 2A, 10-inch pole in a reserve stand of 5,000 board feet on site IV is expected to make an average growth of 4.00 board feet annually over a 30-year period. But as indicated in table 17, such a pole growing on site VI land is expected to make an annual growth of only 4.00 - 2.00, or 2.00 board feet. In contrast, on site II lands such a pole should contribute an annual increment of 4.00 + 2.05, or 6.05 board feet annually. It is also evident that on average site IV lands, poles may make up to 0.40 board feet more growth each year, or 0.70 board feet less, depending on whether the stand in which they grow is lighter or heavier than 5,000 board feet per acre.

FACTORS THAT INFLUENCE TREE MORTALITY

Experience has shown that not every tree reserved for future growth can be expected to survive until the end of the cutting cycle. Thus, in order to estimate the net volume that may be available for cutting at a future date, it is necessary not only to compute the probable rate of tree growth, but it is also essential to make allowance for expected tree loss or mortality.

PLATE III. A pure ponderosa pine stand on the Deschutes National Forest from which was cut 10 years previously, 68 percent by volume. The pole-size trees in the foreground mostly of class 2B and 2C illustrate the "recruits" that are growing into the merchantable size class.

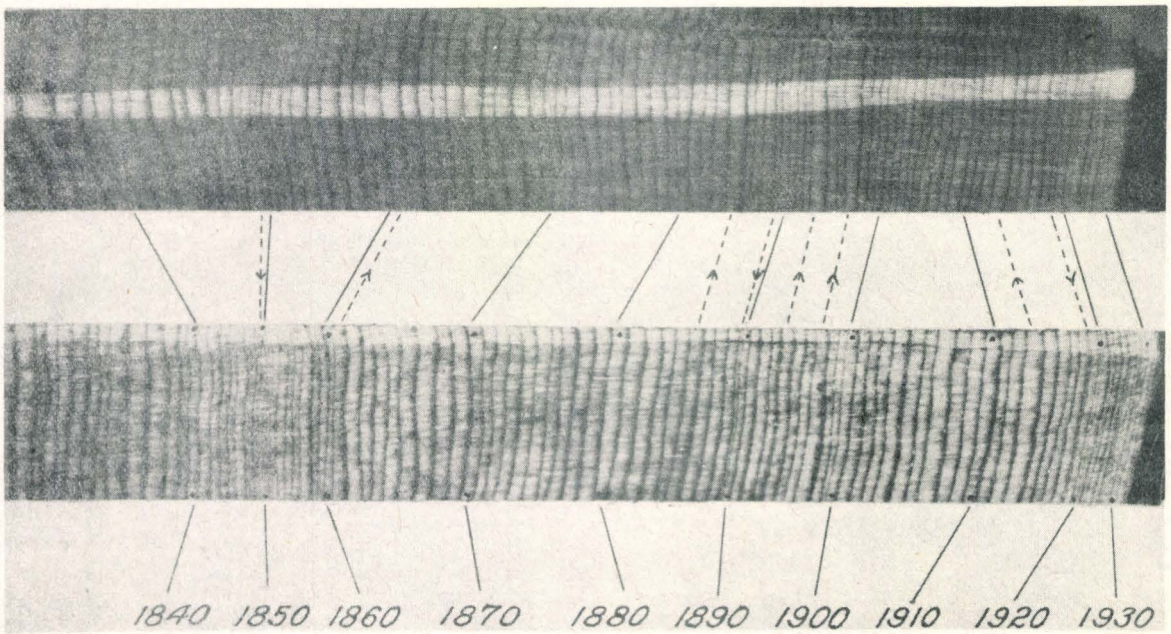


PLATE IV. Radial sections from two ponderosa pines in central Oregon, illustrating periods of rapid and slow growth. The dotted lines connect characteristic wide or narrow rings, which are useful for cross identification. (photo by F. P. Keen)

Table 16.--Average Annual Gross Growth Per Ponderosa Pine Pole in an Average Reserve Stand of Site IV with a Total Volume Per Acre of 5,300 Board Feet. Growth is expressed by Years After Cutting, by Diameter and Keen Tree Classes.

Growth Period	D.B.H. class	Tree class								
		1A	1B	1C	1D	2A	2B	2C	2D	3D
Years	Inches	Board feet, Scribner rule								
10	8	.65				.55				
	10	4.05	2.65	1.25	.75	3.50	2.30	1.80	.60	.45
20	6	.25				.20				
	8	1.50	.60	.15	.10	1.30	.50	.40	.05	
	10	4.40	3.15	1.75	1.05	3.80	2.75	2.20	.85	.70
30	4	.15				.10				
	6	.60	.25			.50	.20	.10		
	8	2.25	1.25	.55	.35	1.95	1.10	.85	.25	.20
	10	4.60	3.55	2.30	1.35	4.00	3.10	2.50	1.15	.90
40	4	.45				.35				
	6	1.05	.80			.95	.70	.50		
	8	2.90	2.00	1.10	.65	2.50	1.75	1.40	.55	.40
	10	4.75	3.90	2.85	1.70	4.15	3.40	2.60	1.40	1.10
50	4	.80				.70				
	6	1.70	1.40	.55	.30	1.50	1.20	.90	.25	
	8	3.40	2.80	1.60	.95	2.95	2.45	1.95	.80	.65
	10	4.85	4.20	3.35	2.00	4.25	3.65	2.90	1.65	1.30
60	4	1.35				1.15				
	6	2.35	2.00	1.10	.65	2.05	1.75	1.30	.55	
	8	3.85	3.55	2.25	1.35	3.35	3.10	2.50	1.10	.90
	10	5.00	4.45	3.90	2.30	4.35	3.85	3.05	1.95	1.50

Table 17.--Corrections for Adjusting Estimated Annual Growth Per Pole For Site and Volume Per Acre of Reserve Stand

Site		Volume per acre (M bd. ft.)												
Index	Quality	0	2	3	4	5	6	7	8	10	12	14	16	24
Feet	Class	Corrections to be added to annual growth per pole, board feet, given in table 15												
50	VI	-1.60	-1.65	-1.75	-1.90	-2.00	-2.10	-2.20	-2.25	-2.40	-2.50			
60		-0.90	-0.95	-1.00	-1.20	-1.30	-1.35	-1.45	-1.55	-1.70	-1.80	-1.90	-1.95	
64	V	-0.60	-0.70	-0.75	-0.90	-1.00	-1.10	-1.20	-1.30	-1.40	-1.50	-1.60	-1.70	
70		-0.20	-0.25	-0.30	-0.45	-0.55	-0.65	-0.75	-0.85	-1.00	-1.10	-1.20	-1.25	-1.30
78	IV	+0.40	+0.35	+0.25	+0.10	0.00	-0.10	-0.15	-0.25	-0.40	-0.50	-0.60	-0.65	-0.70
80		+0.55	+0.50	+0.40	+0.30	+0.20	+0.10	0.00	-0.10	-0.25	-0.35	-0.45	-0.50	-0.55
90		+1.25	+1.20	+1.10	+1.00	+0.90	+0.80	+0.70	+0.60	+0.45	+0.35	+0.25	+0.20	+0.15
92	III	+1.40	+1.35	+1.30	+1.15	+1.05	+0.95	+0.85	+0.75	+0.60	+0.50	+0.40	+0.35	+0.30
100		+2.00	+1.95	+1.85	+1.70	+1.60	+1.50	+1.40	+1.30	+1.15	+1.10	+1.00	+0.90	+0.85
106	II	+2.40	+2.35	+2.30	+2.15	+2.05	+1.95	+1.85	+1.75	+1.60	+1.50	+1.40	+1.35	+1.30
110		+2.70	+2.65	+2.60	+2.45	+2.35	+2.25	+2.15	+2.05	+1.90	+1.80	+1.70	+1.65	+1.60

Figure 9. Alinement Chart for adjusting annual growth per pole for site index and volume per acre.

Table 18.--Average Mortality Ratios by Keen Tree Class In Virgin Forests 1/

Age class	Vigor class			
	A	B	C	D
	Percent	Percent	Percent	Percent
1	.1	.3	.8	1.1
2	.2	.6	1.0	1.5
3	.3	1.0	1.9	2.6
4	.4	1.4	2.7	3.8

1/ Compiled by F. P. Keen from records of loss during the periods 1928-31, 1935-37, and 1939-40.

Keen has shown that the several ponderosa pine tree classes differ widely in their susceptibility to the natural agencies of depletion. This correlation between loss rate and tree age and vigor is shown in the average mortality ratios compiled by him from records on some two hundred 640- and 320-acre plots in virgin stands of Oregon and Washington during 9 years in the periods 1928-31, 1935-37, and 1939-40. Relative rates of loss for the various tree classes are shown by the mortality ratios given in table 18. These mortality ratios also represent annual mortality percentage by tree class that would be expected when total stand mortality averaged 1 percent annually of total stand volume. The normal level of total stand mortality is unknown, and the best estimates of its magnitude that can be made today are crude. During the periods over which Keen's mortality ratios were compiled, average stand mortality actually measured 0.93 percent per year.

A practical present index of normal virgin stand mortality may be derived from the old assumption that in the long run and over large areas loss will equal gross growth. As found by the Forest Survey (1), normal gross annual growth of virgin ponderosa pine stands in central and eastern Oregon and Washington is about 0.67 percent of stand volume. Thus, a rough estimate of normal annual mortality by tree class may be obtained by multiplying Keen's mortality ratios in table 18 by 0.67. The figures resulting from this computation are shown in table 19.

Table 19.--Estimated Annual Mortality Percentage by Keen Tree Class in Virgin Forests 1/

Age class	Vigor class			
	A	B	C	D
	Percent	Percent	Percent	Percent
1	.07	.20	.54	.74
2	.13	.40	.67	1.00
3	.20	.67	1.27	1.74
4	.27	.94	1.81	2.55

1/ Derived by multiplying Keen's mortality ratios in Table 18 by .67, on the assumption that over long periods mortality of all tree classes in the virgin ponderosa pine type averages .67 percent of board-foot volume, the estimated normal gross growth rate for the type at its current average stand structure.

Preliminary computations by Keen indicate that mortality rates may vary by diameter class as well as by tree class, but this suspected correlation has not been defined with sufficient accuracy to warrant application.

Mortality in Selectively Cut Stands

The effect on mortality of relief of stand competition by selective cutting has not yet been satisfactorily determined by direct measurement. Unpublished data by Keen show, however, that change in growth rate and in mortality rate are inversely related. Thus, it is most logical to believe that relief of stand competition by selective cutting should result in a decrease in mortality, perhaps proportionately greater than the corresponding increase in gross increment, if a high order of silviculture is observed in making the cut. If too many of the highly susceptible tree classes, or those of poor growth potentialities, are left in the residual forests, or if the reserve stand is exposed to the elements by too radical release, such desirable results from cutting cannot be achieved. Pending the time when empirical measures of the effect of selective cutting on mortality rates are available, the following arbitrary corrections for given values derived from table 10 and applicable to the rates given in table 19 are proposed for preliminary use:

Growth correction factor for stand competition derived from table 10 (percent)	100	110	120	130	140
Corresponding mortality correction factor (percent)	100	90	80	70	60

These mortality corrections are based on the assumption that mortality is reduced in the same proportion that gross growth rate is increased by relief of stand competition up to 40 percent increase in normal or tabular growth rate. Beyond this point, proportional decrease in mortality rate is not expected, owing to the belief that beyond this limit increased gross growth rate could not be attained without cutting so heavily that increased windfall mortality would overbalance the anticipated drop in insect mortality.

The Salman and Bongberg Risk Rating

The Keen tree classification system, based as it is on age and vigor classes, is particularly well adapted for the estimation of mortality probabilities over periods of several decades. More closely correlated with loss in the immediate future is the Salman and Bongberg (12) risk rating, or current health classification of ponderosa pine trees. By this classification all trees are given one of four risk ratings according to their immediate probability of being killed by insects; these 4 groups of trees are described according to the density, color, distribution, and needle length of the foliage, as follows:

> "Risk I: Low Risk. Foliage of healthy appearance, needles usually long and coarse, color good dark green. Foliage complement (needles per twig) normal or above normal. Few twigs lacking foliage. No weakened portions of crown or dead or dying branches.
>
> "Risk II: Moderate Risk. Foliage mostly healthy, needle length average or better, color fair to good. Foliage complement generally average. Some twigs or branches dying or dead, but such injury not localized to form definite 'weak' spots in crown.
>
> "Risk III: High Risk. Foliage, at least over a considerable portion of crown, average or shorter than average in length, foliage complement on twigs less than normal, thin, bunchy, or unhealthy. Foliage color fair to poor. Some to many twigs or branches lacking foliage, fading, or dead, often localized to form 'weakened' portions of the crown.

"Risk IV: Very High Risk. Foliage mostly unhealthy, needles short, color poor, needle complement sparse over considerable portions of crown. Some to many twigs and branches dead or dying, portions of crown definitely weakened. Active topkilling or partial infestations often present."

Keen has devised a system of determining risk class through a quantitiative valuation of the several factors that make up risk.6/ This consists in giving a "penalty score" to some 18 symptoms of poor tree health which are observable, such as shape, density and vigor of crown, length and color of needles, presence of mistletoe, fire scars or insect activity.

Experience in the use of risk marking indicates that beetle-caused losses of the immediate future can be forecast with considerable accuracy. Thus risk classification provides a means of minimizing losses through the removal of the more susceptible trees by sanitation-salvage cutting. The success of this type of indirect control is attested by numerous operations in recent years. In one case removal of 16 percent of the stand reduced losses more than 70 percent for a 3-year period.

In virgin and in lightly cut ponderosa pine forests, bark beetles are the principal cause of mortality; loss from wind throw is comparatively light. In heavily cut forests wind is the principal cause of mortality and the differences in loss ratios between tree classes are ironed out to some extent. In such forests, i.e., those in which about 65 percent or more of the original stand has been cut, extensive mortality estimates may be made from the relation between gross annual growth per acre and annual loss percent. The following expression of this relationship was computed from measurements made by Meyer on 169 of the sample plots on which his growth study was based:

Loss Percent in Stands of Various Annual Growth Rates

Estimated gross annual growth per acre in board feet of saw-timber reserve stand	20	30	40	50	60	80	100	120	140	160
Estimated annual loss as percent of reserve volume	1.27	1.02	.85	.72	.62	.49	.40	.35	.30	.28

6/ Buckhorn, W. J. Instructions for making barkbeetle surveys in the virgin ponderosa pine stands of Oregon and Washington. Mimeo. Bur. Ent. & Plant Quar. Forest Insect Laboratory, Portland, Ore. June 1944.

Use of the above relationship results in larger estimates of loss for stands of mature and poor-vigor trees than for young, thrifty stands, which is in accord with both reason and experience. Assume, for example, a 5,000 board-foot reserve stand of mature and overmature trees for which gross growth, exclusive of that contributed by the pole stand is 50 board feet. From the above tabulation, the annual mortality per acre for such a stand would be estimated as .0072 x 5,000 board feet, or 36 board feet. In contrast, for an immature or thrifty mature stand of the same reserved volume, namely 5,000 board feet, having an estimated gross annual growth of 80 board feet per acre, the mortality estimate would amount to .0049 x 5,000 board feet, or 24.5 board feet per acre per year.

Other Factors

Mortality is characteristically so highly erratic that its prediction is subject to large error. In addition to the factors considered above, it is influenced by numerous others. During cycles of deficient rainfall and poor growth, Keen has found that insect activity and mortality increase greatly. However, the occurrence or duration of such periods cannot be predicted with sufficient assurance to warrant making separate allowance for the favorable and unfavorable periods when making loss estimates. Thus the best present estimate for any given future period is at the average rate.

After accounting for all measurable factors that influence mortality, considerable variation in loss rate remains. Frequently a large amount of this remaining variation is associated with locality. If, for a particular stand, it is evident that the average mortality rates given above apply poorly, greater accuracy may be obtained by making special, local studies. In making such studies on cut-over areas, however, it should be remembered that abnormally heavy mortality is likely to occur within the first 5 years after cutting, and that measurements of loss over such a period would not apply directly to a longer cycle. Although loss in the reserve stand is likely to be heavier than normal during the years immediately following cutting, so also are the opportunities for salvaging such losses then better than average, and they should not be overlooked.

Data on loss rates of species other than ponderosa pine are very meager. If these species form an important part of the stand, special local study may be justified. Otherwise, arbitrary loss rates that appear appropriate in view of general information regarding tree age, vigor, and exposure will be necessary.

NET GROWTH AND LOSS RATES FOR USE IN SELECTION CUTTING

In the practice of selection cutting in ponderosa pine forests various forms of selection may be employed. The cutting may be light or heavy. It may aim to realize maximum value for each thousand board feet cut or it may forego maximum immediate profits in order to attain the highest quality and quantity of products in subsequent cuttings. The selection cut may merely aim to remove insect susceptible trees and thus lessen probable future losses in advance of the major harvest.

A method of cutting advocated by the Pacific Northwest Forest Experiment Station as sound for both public and private lands has been called the maturity selection system (10) (11). It provides that the trees be selected for cutting in recognition of three factors: (a) growth expectancy, (b) mortality probability and (c) present stumpage value. Thus this method recognizes both silvical and financial consideration. Integrating these three factors, they would be used as a guide in drawing up a local marking rule which would be employed, as should any rule, with judgment by the marker after consideration of each tree. Maturity selection cutting may be either light or moderately heavy, depending on stand structure and the policy and objectives of the owner.

Whatever the particular system of selection cutting may be, good forestry practice dictates that, with certain qualifications, trees of high mortality probability should be selected for early cutting; those of rapid growth rate should be reserved for future harvest. To serve as a guide to the timber marker trying to carry out this policy of selection, rates of estimated annual net growth and loss for the various Keen tree classes and diameter classes have been drawn up in table 20. These rates are applicable to certain conditions in virgin stands on site IV, but they are also useful on a relative basis on other sites and in lightly cut stands. In terms of net rates, the differences between the tree classes are accentuated--the extreme range being from an annual gain of 7.86 percent for the smallest, youngest, most thrifty trees to an annual loss of 2.43 percent for the largest of the oldest, least thrifty trees.

The values are of course for an average tree of a particular diameter and tree class. There is considerable variation in growth rate and character within a single size and tree class, which the tree marker must take cognizance of in selecting trees for cutting or reserving. The average growth rates are a guide which should be used with some flexibility in dealing with non-average trees.

Table 20.--Estimated Annual Net Growth and Loss on Site IV in Virgin Stands as Percent of Board-foot Volume by Tree Class and Diameter Class[1/]

(Red figures indicate net loss)

Diam. at B. H.	Tree class				Tree class				Tree class				Tree class				Diam. at B. H.
	1A	1B	1C	1D	2A	2B	2C	2D	3A	3B	3C	3D	4A	4B	4C	4D	
In.		Percent				Percent				Percent				Percent			In.
12	7.86	5.65	3.96	2.41	5.12	3.65	2.43	1.30			.70	.22				1.55	12
14	4.78	3.37	2.40	1.28	3.67	2.50	1.47	.55		1.11	.18	.32			.86	1.74	14
16	3.31	2.42	1.71	.75	2.75	1.84	.99	.12	1.55	.83	.13	.90			1.04	1.88	16
18	2.56	1.80	1.26		2.20	1.39	.68	.14	1.31	.62	.32	1.09		.21	1.20	2.01	18
20	2.07	1.42			1.81	1.09	.47	.30	1.12	.46	.44	1.22		.29	1.30	2.12	20
22	1.71				1.51	.85	.33		.98	.33	.54	1.31		.35	1.37	2.20	22
24					1.27	.66	.21		.86	.21	.62	1.37	.35	.39	1.42	2.27	24
26					1.08	.51	.11		.76	.11	.70	1.42	.30	.43	1.46	2.32	26
28					.92	.40			.66	.02	.76	1.46	.26	.46	1.49	2.35	28
30					.79	.32			.58	.05	.81	1.49	.22	.50	1.51	2.37	30
32					.69				.51	.10	.84		.18	.53	1.53	2.39	32
34									.46	.15	.87		.14	.57	1.56	2.41	34
36									.41	.19	.90		.11	.60	1.57	2.42	36
38									.38	.22	.92		.08	.63	1.58	2.42	38
40									.35	.24			.05	.65	1.60	2.43	40
42									.32	.26			.03	.67	1.61		42
44									.30	.28			.01	.69	1.62		44
46									.28				.01	.71	1.63		46
48													.02	.73	1.64		48
50													.02	.74			50
54													.03				54
58													.03				58

1/ Derived from tables 6 and 19.

CALCULATING GROWTH OF SPECIFIC STANDS

Up to this point the various factors that affect growth of a pine forest have been considered separately. The study, however, has led to the development of an improved procedure for predicting the growth of specific stands without having to collect numerous increment borings therefrom. It is designed to give proper weight to each of the most important factors affecting growth that were considered above. Each stand for which a growth estimate is desired should be cruised and the following four items of information collected:

1. Area.

2. Stock table, showing average saw-timber volume per acre in trees 11.1 inches in d.b.h. and larger, by species, diameter class, and for the ponderosa pine, by Keen tree class.

3. Average number of poles per acre, i.e. trees 3.1 to 11.0 inches in d.b.h., by species, diameter class, and for the ponderosa pine, by Keen tree class.

4. Site quality class or site index.

The method may be applied to a comparatively small, uniform stand, or to a large and variable tract. In the latter case it is preferable, however, to determine area, stock table, pole stand and site for each major variation in the tract and to make a separate estimate of growth for each.

Practical application of the procedure to a reasonably uniform 100,000-acre virgin ponderosa pine tract being organized for cutting is illustrated below. Present volume on the tract totals 1,131,800,000 board feet. Estimates of net growth (or loss) are desired for the existing virgin stand, and for the anticipated reserve stand.

Growth Estimate for Virgin Stand

Table 21 shows by way of illustration, the saw-timber volume per acre by tree class and diameter class of this virgin forest. The first step in estimating the normal growth rate of this stand is to multiply the volumes in each diameter and tree class by corresponding annual gross growth percentages given in table 6. The detailed result of this computation is given in table 22. The indicated total growth, uncorrected for site and stand competition, is 86.80 board feet per acre per year. As shown in table 22, one of the advantages of this method of growth estimating is that the size and tree class of timber to which growth is being added is immediately apparent.

Table 21.--Volume Per Acre by Diameter and Tree Class of a Sample Virgin Forest

D.B.H.	Tree classes 1 A	1 B	1 C	1 D	2 A	2 B	2 C	2 D	3 A	3 B	3 C	3 D	4 A	4 B	4 C	4 D	Totals
	Board feet, Scribner rule																
12	7	19	7	1	1	12	17	5			8	7				1	85
14	10	24	6		3	31	40	4			16	9			1	2	146
16	11	17	6		14	85	58	5		8	55	15			5	7	286
18	16	16	2		40	136	70	3		45	99	16			15	3	461
20	9	11	2		55	192	39	3	7	97	140	16			17	2	590
22	10	8			100	210	31	3	10	195	251	11		20	34	4	887
24					106	111	23	2	40	450	260	9		45	75	7	1,128
26					75	27	15		100	700	261	6	21	170	81	6	1,462
28					20	14	10		211	516	180		22	200	92	6	1,271
30					32	16			140	492	86		67	230	84		1,147
32					10				215	360	72		74	215	117		1,063
34									161	175	50		130	175	43		734
36									180	171	42		142	240	30		805
38									110	100			120	180	22		532
40									72	70			80	90			312
42									50				45	102			197
44													64	35			99
46													42				42
48													31				31
50													40				40
Total	63	95	23	1	456	834	303	25	1296	3379	1520	89	878	1702	616	38	11,318
				182				1618				6284				3234	

PLATE V. A 40 percent cutting, immediately after felling and before the logs had been removed, in the Blue Mountains of eastern Oregon.

PLATE VI. A hillside on the Malheur National Forest, eastern Oregon, where a 40 percent cut has been made and the logs removed.

Table 22.--Normal Gross Annual Growth Per Acre of Virgin Stand of Saw Timber

	Tree class																
	1				2				3				4				
D.B.H.	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	Totals
Inches	Board feet, Scribner rule																
12	.56	1.11	.32	.03	.05	.49	.53	.12			.16	.11				.01	3.49
14	.48	.86	.18		.11	.90	.86	.06			.23	.10			.01	.02	3.81
16	.37	.45	.14		.40	1.90	.96	.06		.12	.63	.13			.03	.05	5.24
18	.42	.32	.04		.93	2.43	.94	.03		.58	.94	.10			.08	.02	6.83
20	.19	.18	.03		1.07	2.86	.44	.02	.09	1.10	1.16	.08			.07	.01	7.30
22	.18	.10			1.64	2.62	.31	.02	.12	1.95	1.83	.05		.12	.12	.01	9.07
24					1.48	1.18	.20	.01	.42	3.96	1.69	.03		.25	.21	.02	9.45
26					.91	.25	.12		.96	5.46	1.49	.02	.12	.87	.19	.01	10.40
28					.21	.11	.07		1.81	3.56	.92		.12	.96	.18	.01	7.95
30					.29	.12			1.09	3.05	.40		.33	1.01	.15		6.44
32					.08				1.53	2.05	.31		.33	.88	.19		5.37
34									1.06	.91	.20		.53	.65	.06		3.41
36									1.10	.82	.16		.54	.82	.04		3.48
38									.64	.45			.42	.56	.03		2.10
40									.40	.30			.26	.26			1.22
42									.26				.14	.28			.68
44													.18	.09			.27
46													.11				.11
48													.08				.08
50													.10				.10
Totals	2.20	3.02	.71	.03	7.17	12.86	4.43	.32	9.48	24.31	10.12	.62	3.26	6.75	1.36	.16	86.80

This stand occurs on land of site index 79; total volume per acre on the net forested area averages 11,318 board feet, and since it is virgin forest the percent reserve is 100. The correction factor corresponding to these three variables, as read from figure 7, is 106 percent. Thus, corrected gross growth of the saw-timber stand is 86.80 x 1.06, or 92.01 board feet per acre per year.

To compute normal mortality, the total volumes per acre by tree class, given in table 21 are multiplied by the corresponding mortality percentages given in table 19, and the products are totaled. That is, (63 x .0007) + (95 x .0020) + (23 x .0054) . . . etc. . . . . + (38 x .0255) = 83.15 board feet per acre per year.

The next step is to compute the growth in the pole stand. The detailed computations involved are indicated in table 23, at the top of which in section A is tabulated number of trees per acre in the pole stand by d.b.h. and tree class as determined by timber cruise. The next section (section B) shows estimated 20-year mortality percentages by tree class. These are derived by multiplying the annual mortality percentages given in table 19 by 20. In section C is given the number of trees expected to survive 20 years, i.e., present number of trees per acre reduced by expected 20-year mortality. It is to this revised stand table that growth rates per pole given in table 16 are applied. These growth rates, however, are first corrected by the amount indicated in table 17 or figure 9, the correction indicated for site index 79, and a stand per acre of 11,300 board feet, being about -0.400 board feet per pole.

The average growth per 6-inch 1A pole is indicated in table 16 as .25 board feet over a 20-year period, but applying the correction of -.400 indicates that none of the trees in this size and tree class are expected to contribute any board-foot increment within 20 years. Annual growth of the 8-inch 1A trees over the 20 years is computed as: (1.50 - .40) x .21, or .23 board feet. This result is shown in section D of table 23. Continuing thus through the stand table indicates that the pole stand is expected to contribute a total of 4.88 board feet per acre annually over the 20-year period.

Annual growth per acre estimated for the virgin forest may then be summarized:

Gross growth of saw-timber stand	= 92.01	bd.	ft.
Growth of surviving pole stand	= 4.88	"	"
Total gross growth	= 96.89	"	"
Mortality of saw-timber stand	- 83.15	"	"
Estimated net growth	13.74	"	"

Table 23.--Stand Table and Estimated Growth of Poles in Virgin Forest During 20-year Period

D.B.H	Tree class 1A	1B	1C	1D	2A	2B	2C	2D	3D	Totals
In.	Section A. Number of trees per acre at present									
4		.50	.70	.20				.21		1.61
6	.40	.84	2.00	.10		.06	.35	.19		3.94
8	.21	.26	.42	.03	.15	.35	.58	.13	.16	2.29
10	.15	.31	.16		.10	.48	.87	.13	.32	2.52
	.76	1.91	3.28	.33	.25	.89	1.80	.66	.48	10.36
	Section B. Estimated 20-year Mortality Percentage									
	1.40	4.00	10.80	14.80	2.60	8.00	13.40	20.00	34.80	
	Section C. Estimated number of trees per acre surviving 20-year period									
4		.48	.62	.17				.17		1.44
6	.39	.81	1.78	.08		.06	.30	.15		3.57
8	.21	.25	.37	.03	.15	.32	.50	.10	.10	2.03
10	.15	.30	.14		.10	.44	.75	.10	.21	2.19
	.75	1.84	2.91	.28	.25	.82	1.55	.52	.31	9.23
	Section D. Estimated annual growth in board feet per acre on trees surviving 20 years									
4										
6										
8	.23	.05			.14	.03				.45
10	.60	.82	.19		.34	1.03	1.35	.04	.06	4.43
	.83	.87	.19		.48	1.06	1.35	.04	.06	4.88

Table 24.--Stock Table for a Sample Reserve Stand Giving Volume per Acre by Diameter and Tree Class

	Tree classes																
	1				2				3				4				
D.B.H.	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	Totals
	Board feet, Scribner rule																
12	7	19	7	1	1	12	17	5			8	7				1	85
14	10	24	6		3	31	40	4			16	9			1	2	146
16	11	17	6		14	85	58	5		8	55						259
18	16	16	2		40	136	70	3		45	99						427
20	9	11	2		55	192	39	3	7	97	140						555
22	10	8			100	210	31	3	10	195	251						818
24					106	111	23	2	40	450	260						992
26					75	27	15		100	700							917
28					20	14	10		211	516							771
30					32	16			140	492							680
32					10				215	360							585
34									161	175							336
36									180	171							351
38									110								110
40									72								72
42									50								50
Totals	63	95	23	1	456	834	303	25	1296	3209	829	16			1	3	7154
				182				1618				5350				4	

Obviously, this particular stand, for which the expected net growth is about 14 board feet per acre per year, is a slight exception to the theory that for virgin stands as a class, loss will in the long run and over large areas equal gross growth. It is well known, of course, that these two factors are not in a constant state of equilibrium, and this stand should be recognized as having a higher proportion of the younger, more vigorous tree classes than has the average virgin pine forest. In contrast, there are extensive virgin stands, having poorer than average stand structure, in which loss overbalances normal gross growth.

Table 25.--Gross Annual Growth of a Sample Reserve Stand, By D.B.H and Tree Class

D.B.H.	Tree classes 1 A	1 B	1 C	1 D	2 A	2 B	2 C	2 D	3 A	3 B	3 C	3 D	4 A	4 B	4 C	4 D	Totals
	Board feet, Scribner rule																
12	.56	1.11	.32	.03	.05	.49	.53	.12			.16	.11				.01	3.49
14	.48	.86	.18		.11	.90	.86	.06			.23	.10			.01	.02	3.81
16	.37	.45	.14		.40	1.90	.96	.06		.12	.63						5.03
18	.42	.32	.04		.93	2.43	.94	.03		.58	.94						6.63
20	.19	.18	.03		1.07	2.86	.44	.02	.09	1.10	1.16						7.14
22	.18	.10			1.64	2.62	.31	.02	.12	1.95	1.83						8.77
24					1.48	1.18	.20	.01	.42	3.96	1.69						8.94
26					.91	.25	.12		.96	5.46							7.70
28					.21	.11	.07		1.81	3.56							5.76
30					.29	.12			1.09	3.05							4.55
32					.08				1.53	2.05							3.66
34									1.06	.91							1.97
36									1.10	.82							1.92
38									.64								.64
40									.40								.40
42									.26								.26
Totals	2.20	3.02	.71	.03	7.17	12.86	4.43	.32	9.48	23.56	6.64	.21			.01	.03	70.67

Growth Estimate for Anticipated Reserve Stand after Selection Cutting

Let us assume, for example, that the following marking rule is proposed for the above stand:

Cut all 3B trees in the 38-inch d.b.h. class and larger
" " 3C " " " " 26-inch " " " "
" " 3D " " " " 16-inch " " " "
" " 4A "
" " 4B "
" " 4C " in the 16-inch d.b.h. class and larger
" " 4D " " " " 16-inch " " " "

The reserve stand that would remain following such a cut is illustrated in table 24. Its normal gross growth, estimated by multiplying the volumes in this table by corresponding ones in table 6, totals 70.67 board feet per acre per year. (See table 25.) Volume of the anticipated residual stand, which totals 7,154 board feet per acre, represents a 63.2 percent reserve in terms of the virgin stand volume. The correction factor corresponding to these two variables and site index 79, as read from figure 7, is 129.5 percent. Thus, corrected gross growth of the saw-timber stand is 70.67 x 1.295, or 91.52 board feet per acre per year.

Table 26.--Computation of Mortality in a Sample Reserve Stand

Tree class	Volume reserved per acre	Estimated annual mortality per acre		
		In virgin stand	In reserve stand	
	Bd. ft.	Percent	Percent	Bd. ft.
1A	63	.07	.05	.03
1B	95	.20	.14	.13
1C	23	.54	.38	.09
1D	1	.74	.52	.01
2A	456	.13	.09	.41
2B	834	.40	.28	2.34
2C	303	.67	.47	1.42
2D	25	1.00	.70	.18
3A	1,296	.20	.14	1.81
3B	3,209	.67	.47	15.08
3C	829	1.27	.89	7.38
3D	16	1.74	1.22	.20
4C	1	1.81	1.27	.01
4D	3	2.55	1.78	.05
Totals	7,154			29.14

Steps in the computation of mortality in the saw-timber reserve stand are illustrated in table 26. Mortality percentage in the reserve stand has been reduced to 30 percent below that estimated as normal in the virgin stand, or by about the amount that gross growth percent is expected to exceed the normal as a result of relief of stand competition. Estimated annual mortality per acre totals 29.14 board feet.

Computation of growth contributed from the pole stand is summarized in table 27. The steps are essentially the same as those illustrated for the virgin stand. The obvious departures are: (a) a 30-year cutting cycle is assumed, (b) the mortality rates are reduced, and (c) growth rates per pole are increased in anticipation of relief of stand competition by cutting. Expected annual growth per acre of the pole stands totals 7.65 board feet.

Table 27.--Stand Table and Estimated Growth of Poles During 30-year Cutting Cycle

D.B.H.	Tree class									
	1A	1B	1C	1D	2A	2B	2C	2D	3D	Totals
In.	Section A. Number of trees per acre at present									
4		.50	.70	.20				.21		1.61
6	.40	.84	2.00	.10		.06	.35	.19		3.94
8	.21	.26	.42	.03	.15	.35	.58	.13	.16	2.29
10	.15	.31	.16		.10	.48	.87	.13	.32	2.52
	.76	1.91	3.28	.33	.25	.89	1.80	.66	.48	10.36
	Section B. Estimated 30-year Mortality Percentage									
	1.50	4.20	11.40	15.60	2.70	8.40	14.10	21.00	36.60	
	Section C. Estimated number of trees per acre surviving 30-year cutting cycle									
4		.48	.62	.17				.17		1.44
6	.39	.80	1.77	.08		.05	.30	.15		3.54
8	.21	.25	.37	.03	.15	.32	.50	.10	.10	2.03
10	.15	.30	.14		.10	.44	.75	.10	.21	2.19
	.75	1.83	2.90	.28	.25	.81	1.55	.52	.31	9.20
	Section D. Estimated annual growth in board feet per acre on trees surviving 30 years									
4										
6	.17	.06								.23
8	.44	.27	.14		.27	.30	.34	.01		1.77
10	.66	1.01	.30	.01	.38	1.29	1.75	.10	.15	5.65
	1.27	1.34	.44	.01	.65	1.59	2.09	.11	.15	7.65

Estimated annual growth per acre in the reserve stand during the 30 years following cutting is summarized as follows:

Gross growth of saw-timber stand	= 91.52	bd. ft.
Growth of surviving pole stand	= 7.65	" "
Total gross growth	= 99.17	" "
Mortality of saw-timber stand	29.14	" "
Estimated net growth	70.03	" "

Application of Growth Estimates

The discussion to this point has concerned the current rate of growth and that in prospect for the next few decades in virgin forests and selection cut forests. It is interesting now to relate this to the allowable cut that might be made through the first cutting cycle and through the rotation. It is not within the province of this paper to go thoroughly into the matter of regulation of cut and management plans, but the following broad discussion may be helpful to the practicing forester in showing how growth estimates are related to allowable cut.

It is well known to foresters that the sustainable volume of cut is equal to the current rate of growth only in rather exceptional forests. In the typical natural forest allowable cut is greater or less than growth, depending on whether actual volume present is greater or less than that desirable. The relationship of growth to allowable cut under sustained yield is well expressed for selection forests by the familiar Austrian formula which says:

$$\text{Allowable annual cut} = (\text{Annual growth}) + \frac{(\text{Measured volume}) - (\text{Desirable volume})}{\text{n years}}$$

Some of these terms deserve discussion.

Allowable annual cut - the volume of annual timber cut that can be sustained while bringing the forest to its potential level of continuous productivity or maintaining it at that level.

Measured volume is the net content of the present forest as determined by a timber cruise.

Desirable volume is the timber volume contained in a managed forest whose growing stock is balanced by having all age classes up to rotation age equally represented. Volume of growing stock deemed desirable over broad areas is given for various site classes in the last column of table 28 on an average acre basis. Full normal yield table stocking is not synonymous with desirable stocking. Owing to the critical moisture relationships that prevail it is doubtful if most ponderosa pine sites can support in good thrift a full stand by normal yield table standards.

Table 28.--Rotation, Potential Growth, and Desirable Growing Stock for Ponderosa Pine Timberlands, by Site Index and Site Quality Class

Site index	Site quality	Rotation[1]	Potential annual growth per acre[2]	Average volume per acre, balanced growing stock[3]
Feet	Class	Years	Bd. ft.	Bd. ft.
50	VI	210	55	5,000
60		190	80	5,300
64	V	180	90	5,600
70		160	105	5,900
78	IV	140	130	6,600
80		140	140	6,800
90		130	180	8,500
92	III	130	185	8,900
100		120	225	10,300
106	II	110	255	11,300
110		110	275	11,900

1/ Approximate age of maximum mean annual increment of saw timber.
2/ Sixty percent of normal yield table growth rates to technical rotation age.
3/ Sixty percent of normal balanced growing stock to rotation ages indicated.

"n years" represents the period during which an approximately balanced growing stock and the potential growth rate of the site can be attained. In pine stands having a great preponderance of overmature trees, probably 100 to 200 years, or approximately a full rotation, will be required to reach this objective. In exceptional stands, having a nearly uniform distribution of immature age classes, the period "n years" may be no longer than a cutting cycle or two.

Annual Growth. As used in the above formula for allowable cut, "annual growth" represents the weighted average annual net growth for the entire forest over the rotation.

Table 28 also shows the potential mean annual growth which in theory can be attained over the rotations, and with the volume of growing stock indicated. These rates were assumed as estimates of potential growth following an extensive study of increment in natural, even-aged, second-growth stands made as a part of the Forest Survey. They approximate the mean annual increments that have taken place in such stands to about technical rotation age on areas classified as "well stocked." It is recognized that assumed 60 percent normal growth corresponding to 60 percent of normal stocking contains an element of conservatism, owing to the fact that growth rate percent is greater in understocked than in so-called normal stands.

Calculation of Growth for the Entire Rotation

Methods of making detailed growth estimates for the first cutting cycle have been described in a preceding section. Now it is evident that some speculation regarding growth must be carried beyond the first cutting cycle to the end of the rotation. For periods so far in the future, broad assumptions will suffice. If good forestry practices are followed, it seems reasonable to assume that, following the first cycle, growth will increase uniformly toward the expected potential rate.

Application of this line of reasoning to the stand considered above results in the following estimate of weighted average growth rate for the first rotation:

First 30 Years. It is estimated that by light selection cutting, annual net growth for the entire stand will be increased from about 14 to 70 board feet per acre. The average for this period would thus be (14 + 70) ÷ 2, or 42 board feet.

Next 110 Years. If light selection cuts continued to remove the oldest, least thrifty, slowest-growing individuals, the rate of net growth should increase as stand structure gradually improves.

It seems not unreasonable, then, to expect that net growth might thus increase from about 70 board feet per acre at the start of this period to 135 board feet at the end. If this increase occurred at a uniform rate, the weighted average annual growth for this last 110 years of the first rotation would amount to (70 + 135) ÷ 2, or 102.5 board feet per acre per year.

The weighted average growth rate achieved over the entire rotation would then be:

$$\left[(30 \times 42) + (110 \times 102.5)\right] \div 140 = 89.5 \text{ board feet per acre}$$

Now the factors in the formula for allowable cut that apply in the above case can be assembled. For convenience in computation they are expressed on an average acre basis rather than for the total forest area:

Annual growth	=	89.5 Board feet
Measured volume	=	11,318 " "
Desirable volume	=	6,700 " " (This figure is interpolated for site index 79 from table 28)
n years	=	140 (also from table 28)

and

$$\text{Allowable annual cut} = 89.5 + \frac{(11{,}318 - 6{,}700)}{140} = 122.5 \text{ board feet}$$

Since the computations have been carried on a per-acre basis, this is the allowable annual cut per acre of virgin timberland over the first 140-year rotation. This amounts to 1.08 percent of present saw-timber volume, i.e., (122.5 ÷ 11,318) x 100. The proposed marking rule which anticipates the making of a 36.8 percent cut over a 30-year cycle, if carried out, would result in an average annual cut of 36.8 percent ÷ 30, or 1.23 percent of present volume. In terms of the cut indicated as allowable, this amounts to an overcut of about 13 percent for the first 30 years.

As a general principle, no overcut should be made, regardless of how desirable it may seem from other standpoints, without knowledge of the volume of production that could be sustained in following years. This can easily be computed from the information at hand.

Assuming the proposed 36.8 percent cut were made over the first 30 years, the volume remaining on the average acre at the end of that period is estimated at 8,413 board feet, as follows:

Present virgin stand per acre	= 11,318	board feet
30-year cut per acre	= - 4,165	" "
30-year growth on average acre (42x30)	= + 1,260	" "
Estimated volume 30 years hence	8,413	" "

The estimated allowable annual cut to the end of the rotation for the stand that would then remain is:

$$102.5 + \frac{(8,413 - 6,700)}{(140 - 30)} = 118.1 \text{ board feet per acre}$$

After the end of the first rotation, allowable annual cut would presumably equal the rate of potential growth, or 135 board feet per acre. For the entire tract of 100,000 acres, the trend of annual cut thus would be:

First 30 years (cut 36.8 percent of present volume)	=13,880 M bd.ft.
Next 110 years, on sustained yield	=11,810 "
Thereafter, " " "	=13,500 "

In comparison, if limited to the sustainable amount throughout the first rotation, annual cut would be:

First 140 years, on sustained yield	=12,250[7/] M bd.ft.
Thereafter, " " "	=13,500 "

It is evident that if a cut of 13 percent greater than the estimated sustainable amount were made for the first 30 years, the sustained yield cut for the remaining 110 years of the first rotation would be only $3\frac{1}{3}$ percent less than that which could be sustained if this preliminary overcut were not made. Had the overcut during the first cycle been greater, the reduction necessary would have been correspondingly more severe.

Effect of Cutting Practice on Growth and Allowable Cut

From the foregoing simple formula for allowable cut it is clear that any factor which increases the average rate of net growth will aslo increase the volume of annual cut that can be sustained. As computed above, a 36.8 percent selection cut of the oldest, least thrifty trees over a 30-year cycle would be expected to lead to an average first rotation growth rate of 89.5 board feet per acre.

Initial cuttings lighter than this that cover the total forest more quickly have been tried out over quite extensive areas in the Klamath Basin in Oregon and in parts of northern California.

7/ Allowable annual cut per acre under sustained yield times total area of tract, i.e., 122.5 board feet times 100,000= 12,250 M. Bd. Ft.

The Salman risk rating has been the principal basis for tree selection in these experimental "sanitation-salvage" cuts, which have succeeded in removing as little as about 10 percent of the saw-timber stand on a commercial basis. Some sacrifice in stumpage returns has been necessary owing to increased logging costs and to the harvesting of low value trees, but to date the effectiveness in quickly reducing insect mortality has been encouraging.

Some quick measure of the extent to which net growth could be increased by continued application of such light cutting is needed. Obviously, the theoretical maximum rate of increase in net growth would be obtained by spreading each year's cut over the entire forest area, and harvesting all the trees that die from natural causes, as well as a few of the least thrifty, most mature living trees. By so doing, the present gross growth in the virgin stand would be almost entirely and quickly realized as net growth. If net growth then increased at a uniform rate to the potential level at rotation's end, increment over the entire rotation would average:

$$(97 + 135) \div 2, \text{ or } 116 \text{ board feet per acre}$$

This theoretical growth rate of 116 board feet has some practical significance as a measure of the maximum that average net increment could approach under the most intensive of cutting practices during the first rotation. Obviously, the actual that might be achieved by sanitation-salvage or other intensive types of cutting would be somewhat less, and probably closer to the 89.5 board feet estimated for a 37 percent cut than to the 116 board-foot maximum.

Least effective in quickly reducing mortality and increasing net growth over the entire forest area is clear cutting. It is estimated that this method of management on a sustained basis would result in only about 46 board feet per acre average growth rate over the entire first rotation. A comparison of growth trend under light selection and under clear cutting is shown in figure 10.

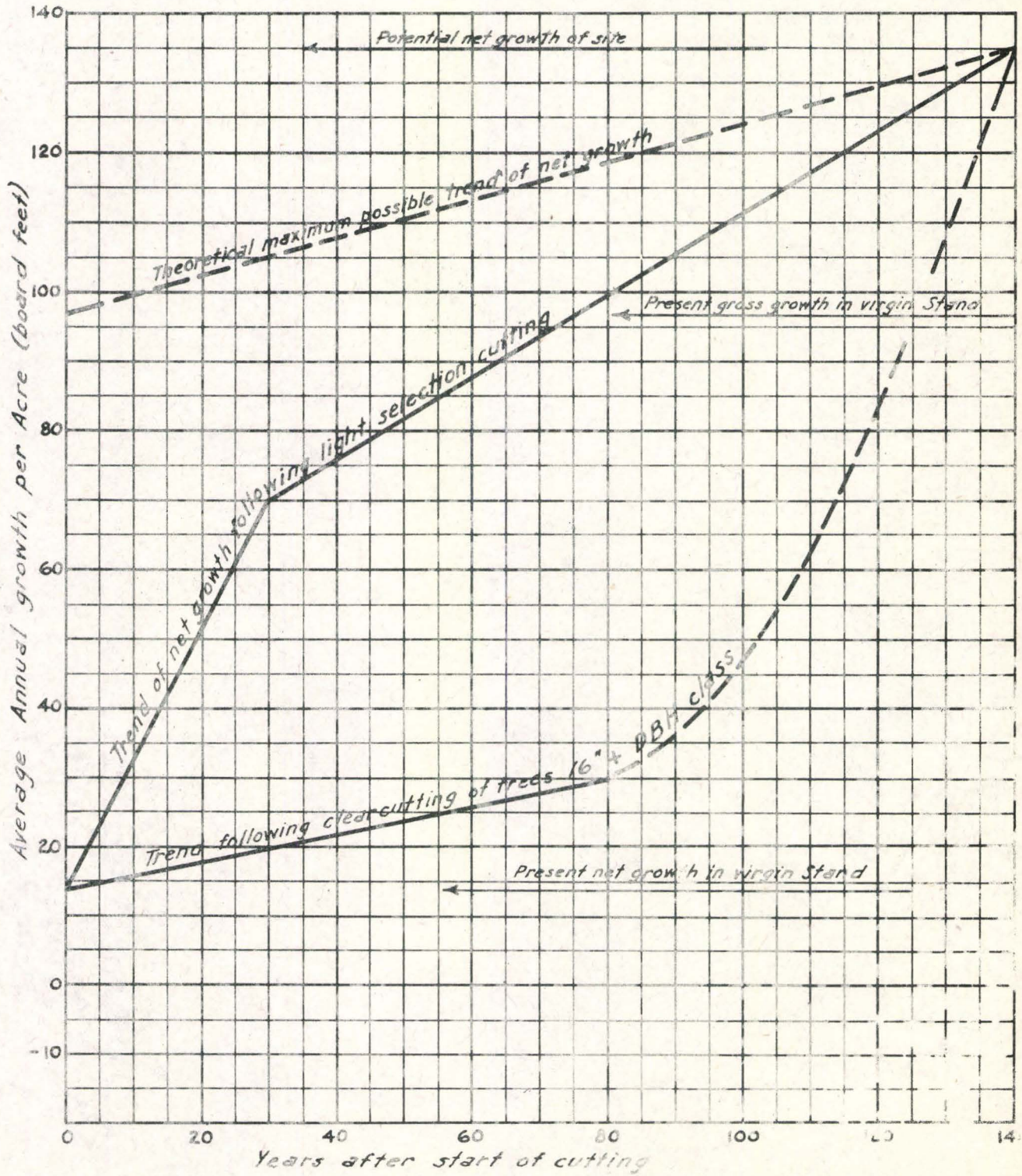
The corresponding effect of cutting practice on allowable cut under sustained yield also is large (see table 29). For the particular 100,000-acre stand under consideration, the annual cut allowable under sustained yield on a clear-cutting basis, 140-year rotation, is about 8,600,000 board feet. In contrast, the same forest could sustain an annual cut of 12,250,000 board feet on a light selection basis, provided that cut were confined to the most mature, least thrifty trees in the stand. These sustainable annual cuts amount to 0.76 and 1.08 percent, respectively, of the present saw-timber volume. The 42 percent increase would be justified under the system of light cutting owing to the increased speed with which net growth is accelerated and mortality is reduced. Theoretical maximum sustained yield cut for the first rotation

Table 29.--Effect of Cutting Practice on Volume of Cut that Could be Sustained During First Rotation

Class of cutting practice	Annual cut that could be sustained		
	Absolute	In terms of present volume	Comparison with theoretical maximum sustainable cut
	M bd.ft.	Percent	Percent
Light selection (30-year cycle)	12,250	1.08	82
Clear cutting of trees in 16-inch D.B.H. class and larger (140-yr. rotation)	8,600	.76	58

is 14,900,000 board feet annually, which could be realized only if all trees that succumb from natural causes were effectively utilized. It is estimated that about 82 percent of this maximum might be realized through light selection cutting, and a slightly higher proportion of the theoretical ceiling might be attained through intensive application of "sanitation-salvage" cuts. In contrast, clear cutting is only 58 percent effective in terms of annual cut that could be sustained thereby.

Fig. 10 Effect of cutting method on trend of average net growth rate of ponderosa pine tract managed on sustained yield basis.



APPENDIX A

Relation of Dunning Tree Class System to the Keen Tree Class System

Within the past decade ponderosa pine tree classification in the Region has changed from the Dunning (4) to the Keen basis. Numerous earlier stand structure cruises, extensive growth studies and management plan calculations have been based on the Dunning classification, and in revising such calculations a knowledge of the general relationship of Dunning to Keen classes will prove helpful.

By definition, the correspondence between the Keen (7) and the Dunning classification is as follows:

Dunning Class	Keen Class
1	1A, 2A
2	1B, 2B
3	3A
4	3B, 3C
5	4A, 4B, 4C
6	1C, 2C, 1D, 2D
7	3D, 4D

Or, conversely:

Keen Class	Dunning Class
1A	1
1B	2
1C	6
1D	6
2A	1
2B	2
2C	6
2D	6
3A	3
3B	4
3C	4
3D	7
4A	5
4B	5
4C	5
4D	7

Actual comparisons have shown that the indicated correspondence should be regarded as a rough approximation. In practice it has been found that each Dunning class includes trees of two or more Keen classes. Thus, it is obvious that the average growth rate of trees in a given Dunning class will depend in part upon the proportion of the two or more Keen classes included, which may vary from stand to stand. In addition contrary to definition, all trees in a given Keen class do not fall within a single Dunning category. For example, it has been found that most trees classed as Keen 2Cs, would if independently rated, fall into the Dunning class 2 instead of the indicated class 6. Some of the better 2Bs will fall into Dunning class 1 instead of class 2, a portion of the most vigorous 3Bs would normally be classed as Dunning 3s instead of 4s. Conversely, the poorer Dunning class 3s will usually fall into the Keen 3B category.

Classification of trees under the Keen system became a common practice before coordinated growth data by Keen class were available. By using Keen class stand structure information and roughly corresponding Dunning class growth rates empirical estimates of growth for the total stand were obtained. The following tabulation is illustrative of the expediencies that previously have been thus employed:

Keen Tree Class	Dunning Class Growth Rate Employed
1A, 2A	Tree class 1
1B, 2B, 2C	" " 2
1C, 1D, 2D	" " 6
3A	" " 3
3B	" " 4 x (1.10)
3C	" " 4 x (0.95)
3D	" " 7 x (1.05)
4A	" " 5 x (1.05)
4B	" " 5
4C	" " 5 x (0.90)
4D	" " 7 x (0.75)

Recent tests indicate that considerable discrepancies between estimated and measured growth rates for the several tree classes may thus result. However, these differences have been largely compensating, and, the procedure generally has given useful preliminary growth rates for the total stand.

APPENDIX B

Relation of Bark Thickness to Diameter Increment

In 1941 Keen and Grant made 1,437 bark thickness measurements on permanent growth plots, from which a multiple correlation of bark thickness with diameter, age, and vigor was computed. The formula, cited in the preceding text is as follows:

Double bark thickness at breast height in inches =
.0787 d.b.h. ob. - .1615 age class - .1235 vigor class + 1.981

The vigor classes are expressed by the numerical values 1, 2, 3, and 4 for vigor classes A, B, C and D, respectively.

Translated into words, this formula says: (1) For trees of a given age and vigor class, bark is thicker, by a specified amount, the larger the d.b.h.; (2) for trees of a given size and vigor, bark is thinner the older the tree; and (3) for trees of a given size and age, bark is thinner the poorer the vigor. Bark thickness of ponderosa pines of any tree class and for any reasonable d.b.h. within that class can be computed by this equation. For example, that for a 25-inch 3B tree is estimated as:

(.0787 x 25) - (.1615 x 3) - (.1235 x 2) + 1.981 = 3.217 inches.

Based on d.b.h., inside bark, the equation for bark thickness is:

Double bark thickness at b.h. (inches) =
.08542 d.b.h. ib. - .1615 age class - .1235 vigor class + 2.0869

An example will serve to illustrate the use of these equations for estimating the growth of bark that normally accompanies a given increase in diameter of wood. Take, for example, a 17-inch 2B tree, for which the estimated normal d.b.h. growth of wood for the next 20 years is 1.82 inches.

The present d.b.h. ib. of this tree is estimated as:

17 inches - present double bark thickness, or
17 - (.0787 x 17 - .1615 x 2 - .1235 x 2 + 1.981) = 14.25 inches

During the 20 years the d.b.h. ib. is expected to increase from 14.25 inches to 14.25 inches + 1.82 inches, or to 16.07 inches. Let us assume that during this 20-year period vigor class remains the same, i.e., class B. Age class, however, will increase 20 ÷ 100 or .2 of a class interval to 2.2. Then, d.b.h. ob. 20 years hence would be estimated as:

16.07 + (.08542 x 16.07 - .1616 x 2.2 - .1235 x 2 + 2.0869)=18.93 inches

If growth of wood only had been allowed for, d.b.h. ob. 20 years hence would have been estimated merely as 17 inches, the present d.b.h. ob. + 1.82 inches, the estimated growth of wood, or 18.82 inches. The difference in estimated growth of diameter outside bark is 1.93 inches - 1.82 inches, or .11 inches, an increase of 6 percent, due to the allowance for growth of bark.

Sample plot examiners express surprise at trees that decrease in d.b.h. measurement between examinations. Such occurrences usually have been rightly attributed to errors of measurement, but the above bark thickness equations indicate that diameter shrinkage may sometimes be real and logical.

Let us take, for example, a 20-inch, class 3C of waning vigor. Such a tree, if it survives, will make a d.b.h. ib. increment of perhaps .05 inches per decade as it declines into the next lower or D-vigor class. The first equation indicates present double bark thickness of this tree is:

$$(.0787 \times 20) - (.1615 \times 3) - (.1235 \times 3) + 1.981 = 2.70 \text{ inches}$$

Present d.b.h. ib. would then equal 20.00 - 2.70 or 17.30 inches. If d.b.h. ib. grows to 17.35 inches during the next decade while vigor drops to class D, bark thickness 10 years hence would be estimated as:

$$(.08542 \times 17.35) - (.1615 \times 3.1) - (.1235 \times 4) + 2.0869 = 2.57 \text{ inches}$$

in which the age increase of 0.1 class and vigor decrease of 1 class is indicated by 3.1 and 4 respectively.

The present dimensions of this tree and those estimated for 10 years hence are tabulated below:

Time	Tree class	D.B.H. ob.	D.B.H. ib.	Bark thickness
Now	3C	20.00	17.30	2.70
10 years hence	3D	19.92	17.35	2.57

The equations indicate that loss of bark by sloughing would exceed bark increment from cambial activity during a period of such slow growth, and that d.b.h. ob. would actually shrink even while d.b.h. ib. make a small increase.

Allowance was made for growth of bark in the growth estimates by the following equation which was derived from the two above:

10-year growth in d.b.h. ob. =
1.08542 (10-year growth in d.b.h. ib.) - .01615.

LITERATURE CITED

(1) Briegleb, P. A.
1940. Forest growth in the ponderosa pine region of Oregon and Washington, Pacific Northwest Forest Experiment Station. Forest Survey Report No. 78. 51 pp., illus., processed.

(2) _____
1943. Growth of ponderosa pine by Keen tree class. Pacific Northwest Forest Experiment Station. Forest Research Notes No. 32, 15 pp., illus., processed.

(3) Cowlin , R.W., Briegleb, P.A., and Moravets, F.L.
1942. Forest resources of the ponderosa pine region of Washington and Oregon. U.S. Dept.Agric.Misc.Pub. No. 490, 99 pp., illus.

(4) Dunning, Duncan.
1928. A tree classification for the selection forests of the Sierra Nevada. Jour. Agr. Research 36: 755-771, illus.

(5) Keen, F. P.
1936. Relative susceptibility of ponderosa pines to bark beetle attack. Jour. Forestry 34: 919-27, illus.

(6) _____
1937. Climatic cycles in eastern Oregon as indicated by tree rings. U.S. Monthly Weather Rev. 65: 175-188, illus.

(7) _____
1943. Ponderosa pine tree classes redefined. Jour. Forestry 41: 249-253, illus.

(8) Meyer, Walter H.
1934. Growth in selectively cut ponderosa pine forests of the Pacific Northwest. U.S. Dept. Agric. Tech. Bul. 407, 64 pp., illus.

(9) _____
1938. Yield of even-aged stands of ponderosa pine. U.S. Dept. Agric. Tech. Bul. 630, 60 pp., illus.

(10) Munger, Thornton T.
1941. They discuss the maturity selection system. Jour. Forestry 39: 297-303.

(11) _____ and Briegleb, P.A.
1942. Recent developments in pine silviculture. Northwest Science 16: 40-45.

(12) Salman, K.A., and Bongberg, J.W.
1942. Logging high-risk trees to control insects in the pine stands of northeastern California. Jour. Forestry 40: 533-539.